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FRICTION AND WEAR AT HIGH SLIDING SPEEDS

BENET WEAPONS LABORATORY
WATERVLIET ARSENAL
WATERVLIET, N.Y. 12189

JUNE 1975

TECHNICAL REPORT

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The wear of rotating band materials and projectile steel at very high sliding speeds is of great importance in the development of improved cannon. This is especially true for the large caliber, high muzzle velocity weapons where excess wear on the bore near the muzzle can limit their useful lives. An extensive experimental study by The Franklin Institute was supported by the Army from about 1946 to 1956 with a great deal of data collected at sliding speeds up to 1800 fps using a sophisticated high-speed-pin-on-disk test device. These data indicated that the mechanism of wear at high sliding speeds

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20. is surface melting followed by subsequent removal of a portion of the melted surface layer. This means that a rotating band material must be high melting if it is to have good wear resistance at high sliding speeds although, of course, wear can be decreased by design changes such as increased bearing area, etc. This does not mean, however, that compatibility, crystal structure, hardness, etc. have no effect because, for a short distance down the bore, the surface of the rotating bands is not completely melted. It could be that excessive bore wear near the muzzle actually is caused by severe wear of the rotating bands occuring near the origin-of-rifling in some cases.

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FRICTION AND WEAR AT HIGH SLIDING SPEEDS

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Introduction

The sliding of a projectile down a cannon bore may reach velocities as high as 5,000 fps. Therefore, the wear of rotating band materials and projectile steel at these very high sliding speeds is of great importance in the development of improved cannon. This is especially true in the case of the large caliber, high muzzle velocity weapons where excess wear on the bore near the muzzle can limit their useful lives. This is the location where radial loading and projectile velocity is greatest. Radial loading is chiefly caused by obturation failure and centrifugal force due to "cocking" of the projectile in the bore and to any unbalance which may be present in it. "Cocking" of the projectile in itself will not result in excess muzzle wear if it is not too great; all projectiles tend to be "cocked" to the maximum extent allowed by their designs and the wear on the rotating bands. However, as the bands wear, the projectile becomes more and more eccentric which leads, in turn, to higher loading and still more wear until the steel projectile shell slides directly on the steel bore. This situation results in very high radial loading and to the sliding of a relatively hard surface on the gun steel bore at speeds near the muzzle velocity and consequentially to excessive bore wear at this location.(1)

The mechanism and relative wear rates of materials at these very high sliding speeds is also of importance in many other applications but there has been little research published on this subject because of the difficulty of the experimental problems. An extensive

1 R.S. Montgomery, Muzzle Erosion of Cannon, Watervliet Arsenal Report 74050, (Nov. 1974)

experimental study by The Franklin Institute[2-13] was supported by the Army from about 1946 to 1956 with a great deal of data collected at sliding speeds up to 1800 fps using a sophisticated high-speed pin-on-disk test device. However, there was no publication of the work in the open literature because it was classified at the time and it has largely been forgotten by research workers.

In this report, The Franklin Institute friction and wear data has been collected and presented in a form which will be useful to scientists and engineers and which also allows an insight into the wear mechanism of rotating bands at high sliding speeds and suggests solutions to the problem of excess rotating band wear.

Experimental Technique

An experiment consisted of contacting a small pin of the test material simultaneously on each face of the rim of a rotating gun steel disk two feet in diameter. The chemical analysis of the disk steel is given in Table I. The specimens were moved radially with just enough velocity to make them follow a non-overlapping spiral path on successive revolutions of the disk. Load was applied to the pins by means of

[2-13] The Franklin Institute Reports I-1858 (Sept. 1948), P-1858-19 (Dec. 1948), P-1858-20 (Feb. 1949), P-1858-22 (Mar. 1949), P-1858-25 (Jun. 1949), F-1996 (Nov. 1949), I-2358-8 (Apr. 1954), I-2448-1 (Mar. 1955), I-2488-2 (Jun. 1955), I-2448-3 (Jan. 1956), F-2448 (Aug. 1956), I-2358-3 (Apr. 1954).

air pressure acting through a combination of pistons and cams. The specimen holders ride on the cams except while the pins are transversing the rim of the disk, when they are let down at one edge of the rim and picked up before they reach the other edge. A diagram of the apparatus is shown in Fig. 1. Pins of 0.08 in. diameter were used for all but a few experiments. To reduce windage losses, tests at disk speeds above 600 fps were made with reduced pressure in the test chamber. The chamber, which was below ground level, remained at an air temperature between 60° and 65°F at all times. The relative humidity, measured in the laboratory above the test equipment, varied between 30 and 90%.

The frictional and normal forces on the pins were measured continuously by means of strain gages bonded to the specimen holders. The holders were flexible enough to give easily measurable deflections. In the early experiments, the amplified signals were sampled with a four-channel electronic switch, displayed on an oscilloscope, and photographed with a 35mm single frame camera. In later experiments, the amplified signals were displayed on a four-channel oscilloscope and photographed with a drum camera. Just before and after a test, calibration marks were also photographed. These were obtained by inserting known resistances into the strain gage bridges. The first experiments produced coefficients of friction which were much too low owing to problems with the instrumentation. These friction data are not tabulated. After the problems were corrected, the friction data were stated to be accurate.

Temperatures of the specimens were measured continuously during the experiment by means of thermocouples of various designs but these measurements were largely unsatisfactory. In addition to the measurements of forces and temperature, an accurate time signal was included at frequencies of 1, 3, 5 or 9 kc. Wear was determined by measuring the weight or length loss of the lower pin. Wear measurements from the upper pin were not considered reliable because of possible contamination of this surface with oil from the shaft seal. In some of the experiments with gilding metal and annealed iron, a gradually increasing load was applied to the pins during the experiments. In these experiments, of course, there were no wear measurements, and, furthermore, some of the friction measurements appeared to be unreliable and so were not used in the present work.

The condition and reproducability of the steel disk surface was of major importance. It was prepared using a number of different methods during the course of the experimental work which extended over about ten years. It was rubbed with emery cloth and wiped with dry cheesecloth; ground and wiped with dry cheesecloth; ground and swabbed with absolute alcohol; rubbed with emery cloth and swabbed with acetone; or, in the later experiments, rubbed with 120 grit emery, swabbed with acetone, and then rubbed with 240 grit emery. This latter procedure produced the most reproducible test surface. The wear of pins of gilding metal, copper, and projectile steel and the friction of these metals and annealed iron on gun steel were extensively investigated. In addition, there were a few experiments with pins of other materials. The chemical analyses of these materials are given in Tables II, III, IV, V, and VI.

Friction

The coefficients of friction of gilding metal, copper, annealed iron, and projectile steel as functions of the product of bearing pressure and velocity are shown in Figs. 2, 3, 4, and 5, respectively.* Provided that the mechanism of interaction of the sliding surfaces is the same, the chief effect of both increased bearing pressure and increased velocity on the coefficient of friction is through the raising of the surface temperatures. Although definite evidence of surface melting was found only with the relatively low-melting metals, copper and gilding metal (9, 12), the characteristics of the friction curves indicate that the surface layers of all the metals melt at high values of PV.

The existence of surface melting is brought out more clearly by plotting the coefficients of friction against the rate of heat generation. (Figs. 6, 7, 8, and 9) This is equal to the product of coefficient of friction, bearing pressure, and velocity. Very high friction coefficients and oscillations were observed at low values. When the rate of heat generation was high enough, the coefficient of friction assumed a stable, relatively low value indicating a different surface character which was, without much doubt, a completely melted surface layer. It seems evident that below this, the heat was insufficient to completely melt the surface.

The unstable, high coefficient of friction region extends to much greater values for copper (Fig. 7) than for the other

*Actual firing data indicate somewhat lower values than those measured in this study.

metals investigated. The chief reason for this is probably that the bearing pressure was actually much lower than calculated owing to "mushrooming" of the soft, small diameter test pins.

At PV values greater than about 3,000,000 (psi)(fps), the friction coefficients were in the range 0.29 - 0.34 and were reproducible and stable. Above this PV value, the friction coefficients for gilding metal and annealed iron were essentually the same while the coefficients for copper were somewhat higher and those for projectile steel still higher. They all decreased with increasing PV with the coefficients for gilding metal and annealed iron decreasing more rapidly. There were insufficient determinations on the other materials investigated to allow firm conclusions about their coefficients of friction. However, the few data indicated that the coefficients of friction for aluminum and zinc were probably similar to those of copper and the coefficients of friction of constantan similar to those of gilding metal. The coefficients of friction for nylon appear to be substantially lower than those for the other materials investigated.

Wear

All the wear rates in this report were determined by weight loss of the test specimens. Length loss was also measured but could not be used for wear determinations with the softer metals because the small diameter pins deformed during the experiment. Length loss as a function of weight loss for gilding metal, copper, and projectile steel are plotted in Figs. 10, 11, and 12, respectively, together with the straight lines calculated with the assumption that there was no distortion. From these figures it can be seen that the copper pins deformed severely, the gilding metal pins deformed moderately, and the projectile steel pins were essentially undeformed. This corroborated visual observations on the pins after the experiments. The soft copper pins were greatly "mushroomed". This had the effect of producing an artificially low wear rate for any particular PV value because the bearing area was actually much greater than that calculated for a 0.080 in. diameter pin. There was also a great deal of scatter in the data for the soft copper, less in the data for the harder gilding metal, and essentially none in the data for the still harder projectile steel. This data scatter for the soft pins would be predicted because the experiments were made with widely different loads.

The wear data for both copper (Fig. 13) and projectile steel (Fig. 14) show the same general features. There were very high and inconsistent wear rates below PV values of about 3,000,000 (psi)(fps) after which the wear rates became much lower. They then increased smoothly with PV to the highest values investigated. The gilding metal data, the first data obtained in the study, showed so much scatter that it was difficult to discern the trend. However, the wear characteristics of gilding metal are doubtlessly similar to those of copper and projectile steel.

The region of rapid wear at low PV values corresponds with the region of high and unstable friction. As stated above, this is probably a result of only partial surface melting. As the heat generation increases, the surface completely melts and both friction and wear rate assume stable, much lower values.

Wear rate at high sliding speed is a function of the rate of heat generation. At values greater than about 1.2×10^6 (psi)(fps), the experimental wear data for both copper and steel can be well-fitted by equation (1),

$$(WR) = \text{Const.}\ (fPV)^2 \qquad (1)$$

This is shown in Figs. 15 and 16 where wear rates are plotted as functions of the rate of heat generation; at high values of heat generation, the wear rates fall on a straight line (log-log plot) of slope 2.

Furthermore, a semi-log plot of the wear rates of the individual materials at a particular rate of heat generation as functions of the reciprocals of their absolute melting points produces a straight line with the higher melting materials showing the lower wear rates (Fig. 17). This indicates that the constant in equation (1) can be expressed by the following equation:

$$\text{Const.} = A\ e^{B/T_m} \qquad (2)$$

where A and B are constants and T_m the absolute melting point. The wear rates for copper and projectile steel were obtained from Figs. 15 and 16, respectively. The value for gilding metal was estimated from the experimental data. The remaining wear rates were estimated from the few data in Table XI using equation (1). The pin diameter used for most of the experiments in Table XI was 0.140 in. which is appreciably larger than the 0.080 in. used for the other experiments. This tended to eliminate problems caused by distortion of the test pins during the experiment. For constantan, the wear rate at the higher velocity and bearing pressure was used in the estimation because it is probable that the surface would not be completely melted for a material melting at 1553°K at a rate of heat generation of only 0.84. In the other cases, the arithmetical averages were used.

There was little scatter considering the paucity of the experimental measurements for most of the data points. Only the points for nickel and copper are seriously out of place. There was only a single determination with nickel and the 0.74 rate of heat generation, judging from the results with steel which has a similar melting point, is not high enough to ensure complete surface melting. Therefore, it is not surprising that the wear rate is higher than expected. The wear rate for pure copper was much lower than expected. This was probably largely a result of the fact that the bearing pressures were appreciably lower than those calculated because of "mushrooming" of the test pins. However, it is also plausible that the extremely high thermal conductivity of pure copper would result in heat being rapidly carried away from the sliding surface and the material behaving as if it were higher melting than it actually is. Its conductivity is almost twice that of aluminum, the next most conductive material studied.

Conclusion

A very important conclusion from this work is that the mechanism of wear at high sliding speeds is almost certainly surface melting followed by subsequent removal of a portion of the melted surface layer. This means that factors such as compatability, crystal structure, hardness, etc. play absolutely no part in this sort of wear. The surfaces are not actually in contact at all but are separated by a lubricating film of melted material. Excluding metallurgical reactions which have been shown to be important in some cases[14], the wear rate depends only on the thickness and viscosity of the melted layer so is almost entirely a function of the melting point. Thermal conductivity, etc. will have effects but they will be minor as long as the values are not grossly different. There is a possibility, for example, that pure copper could be acting as if it were higher melting than it actually is owing to the rapid conduction of heat away from its surface. Pure copper, however, has almost twice the thermal conductivity of aluminum, the next most conductive material studied. Of the materials studied, with the possible exception of pure copper, there was no indication that any property other than melting point had a significant influence on wear rate at high sliding speeds. Therefore, a rotating band material must be high melting if it is to have good wear resistance at high sliding speeds although, of course, wear can be decreased by design changes such as increased bearing area, etc.

From the above discussion, it cannot be concluded that the usually important properties such as compatibility, crystal structure, etc. will not be important in the problem of excessive rotating band wear. For a short distance down the bore, the surface of the rotating

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[14] R.S. Montgomery, Interaction of Copper-Containing Rotating Band Metal with Gun Bores at the Environment Present in a Gun Tube, Wear, 33, 109-128 (1975); Watervliet Arsenal Report 74016 (Jun. 1974).

bands is not completely melted and these factors would be important there. There is an indication in the experimental data that some materials wear many times more rapidly in the initial phase of the sliding than do others. It could be that excessive bore wear near the muzzle actually is caused by severe wear of the rotating bands occurring near the origin-of-rifling in some cases. Therefore, it seems likely that an important research area would be this initial phase of the sliding.

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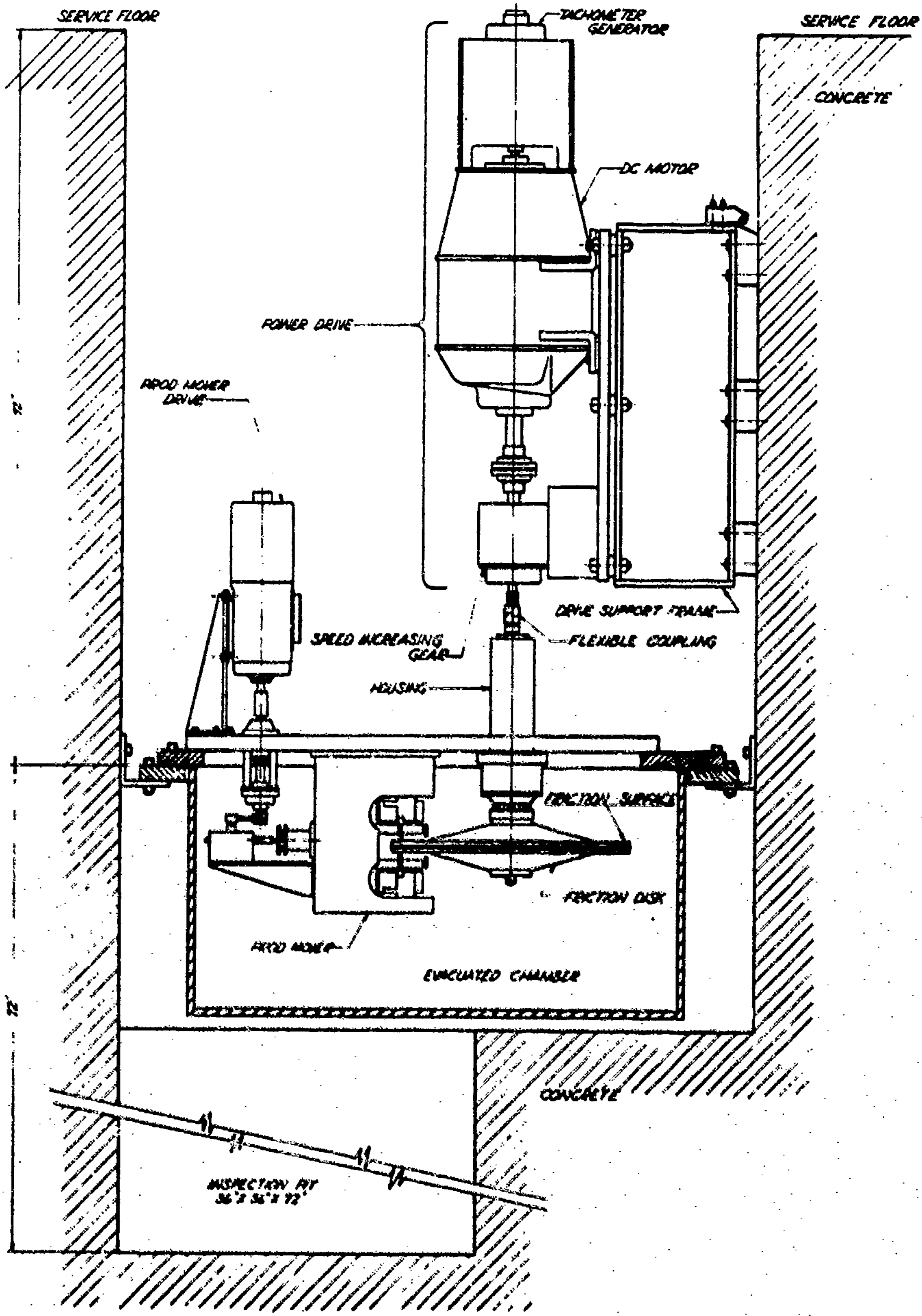

Fig. 1 Schematic Assembly of Friction Machine

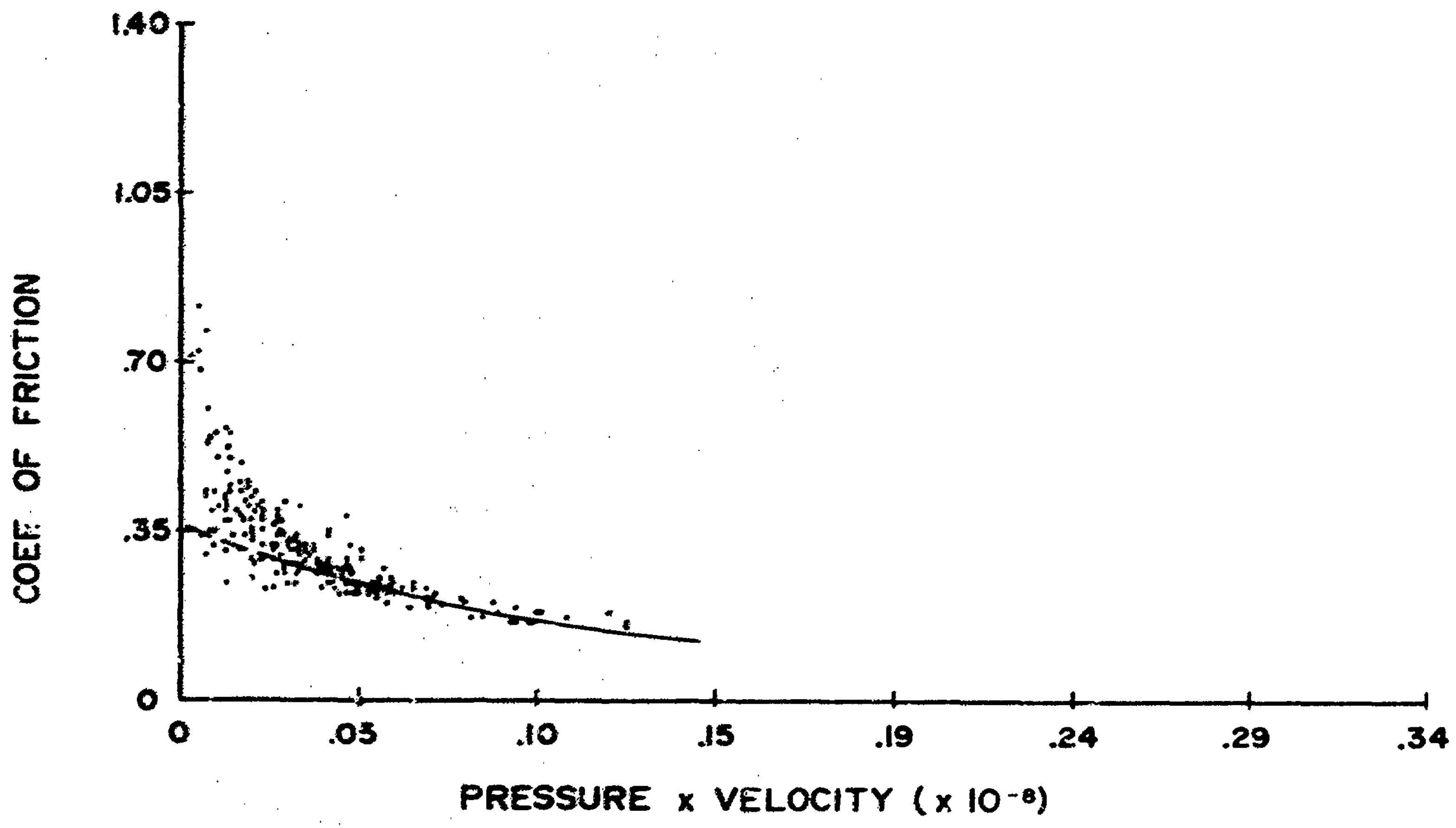

Fig. 2 Coefficient of Friction of Gilding Metal as a Function of Pressure x Velocity (psi) (fps)

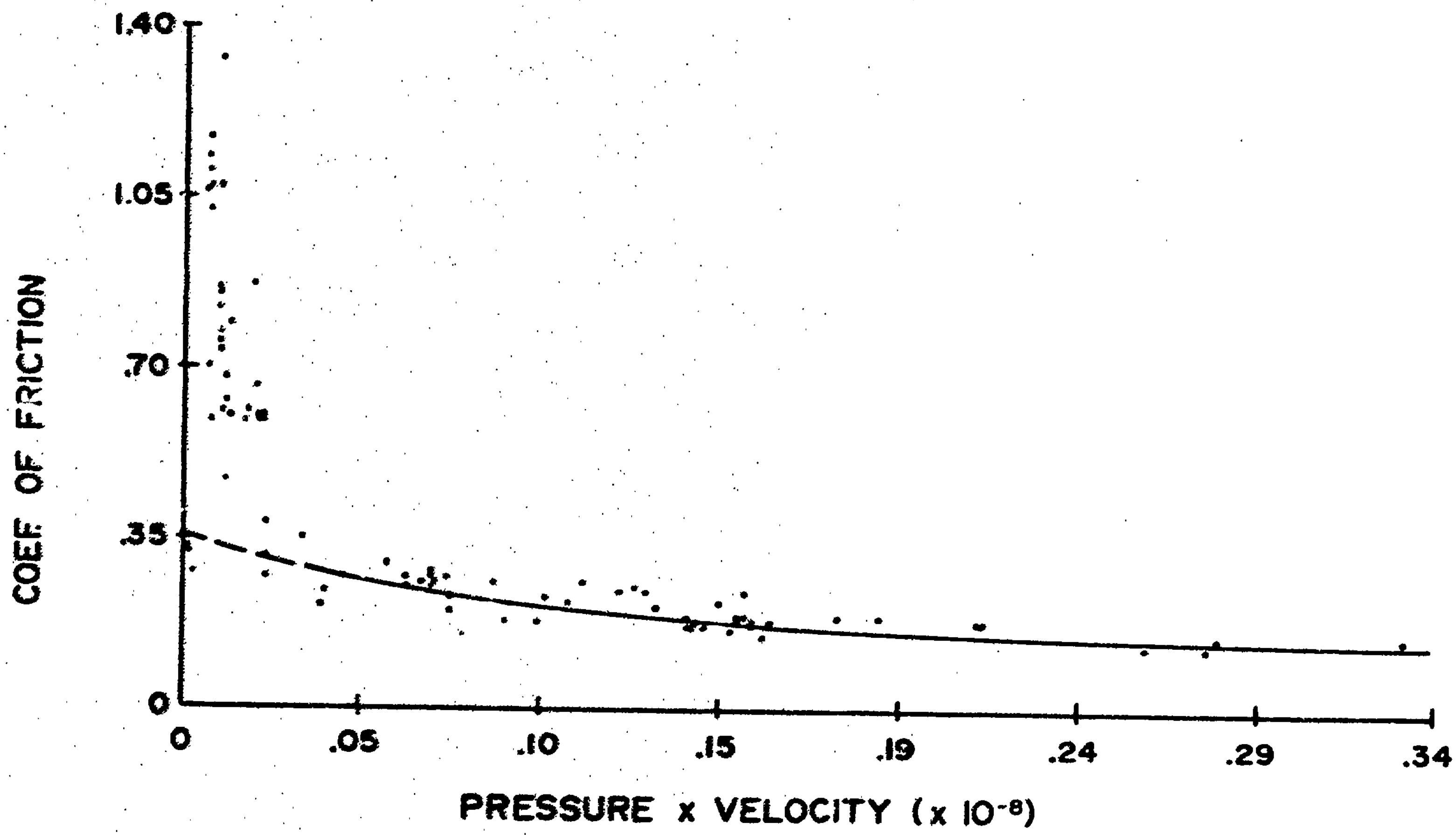

Fig. 3 Coefficient of Friction of Copper as a Function of Pressure x Velocity (psi) (fps)

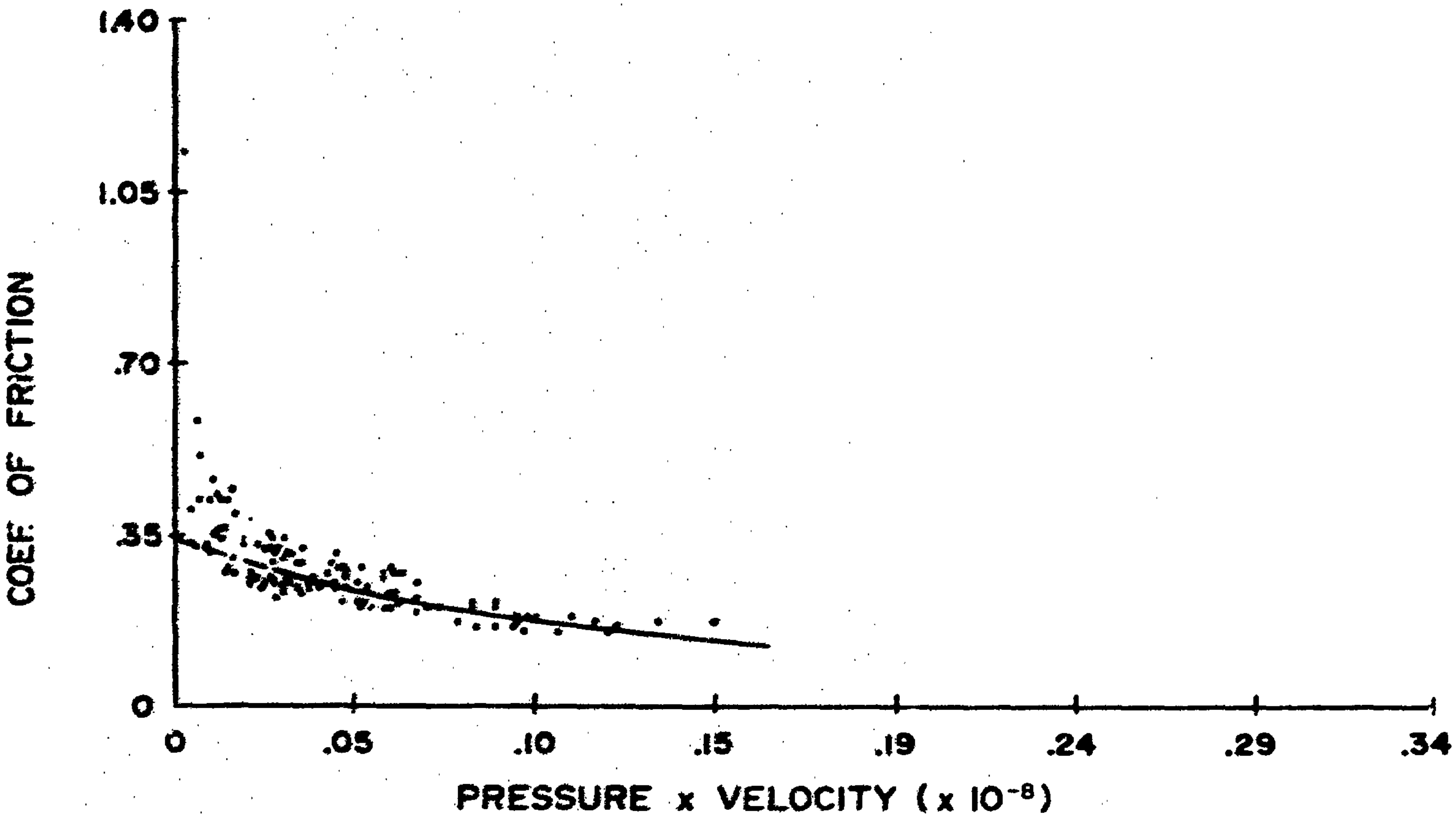

Fig. 4 Coefficient of Friction of Annealed Iron as a Function of Pressure x Velocity (psi) (fps)

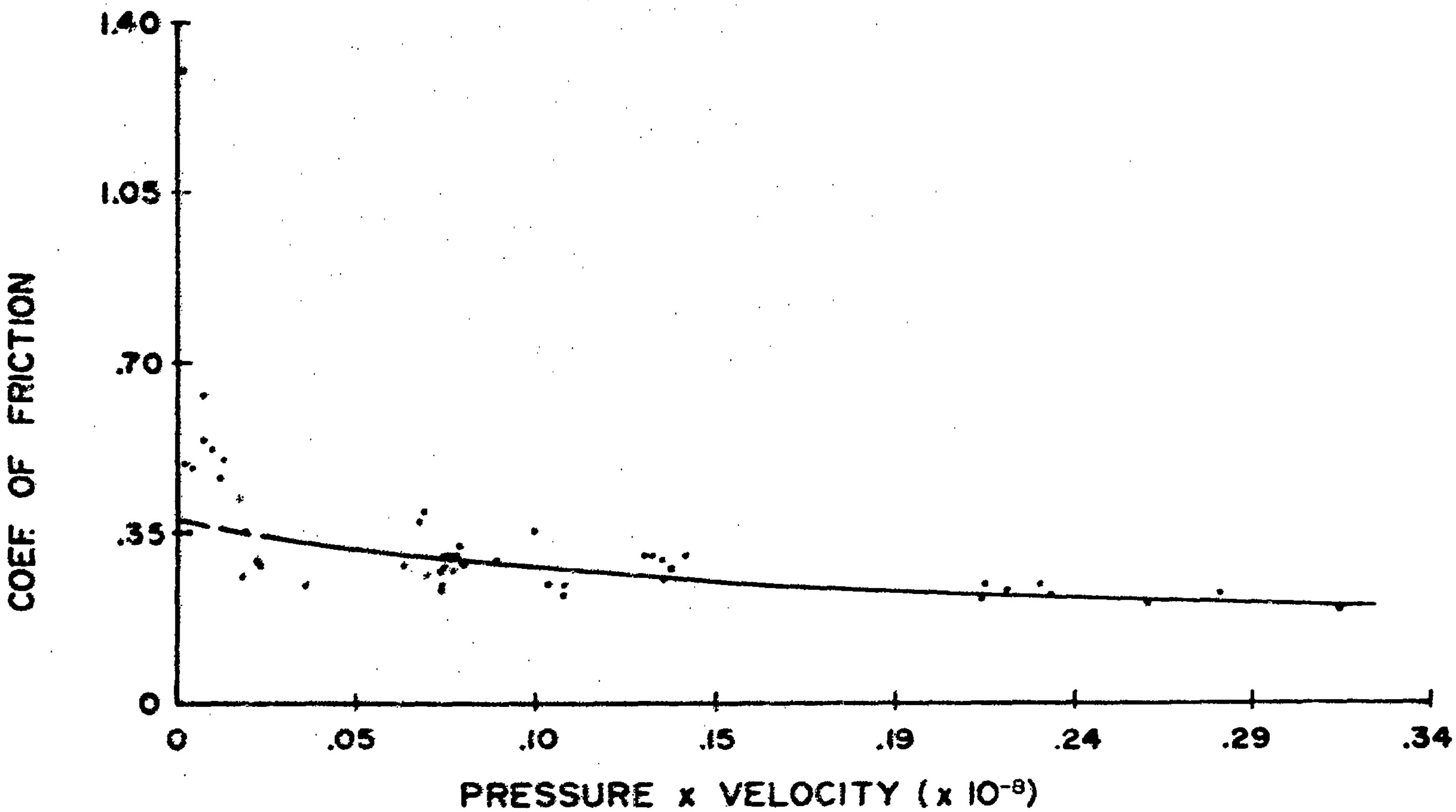

Fig. 3 Coefficient of Friction of Projectile Steel as a Function of Pressure x Velocity (psi) (fps)

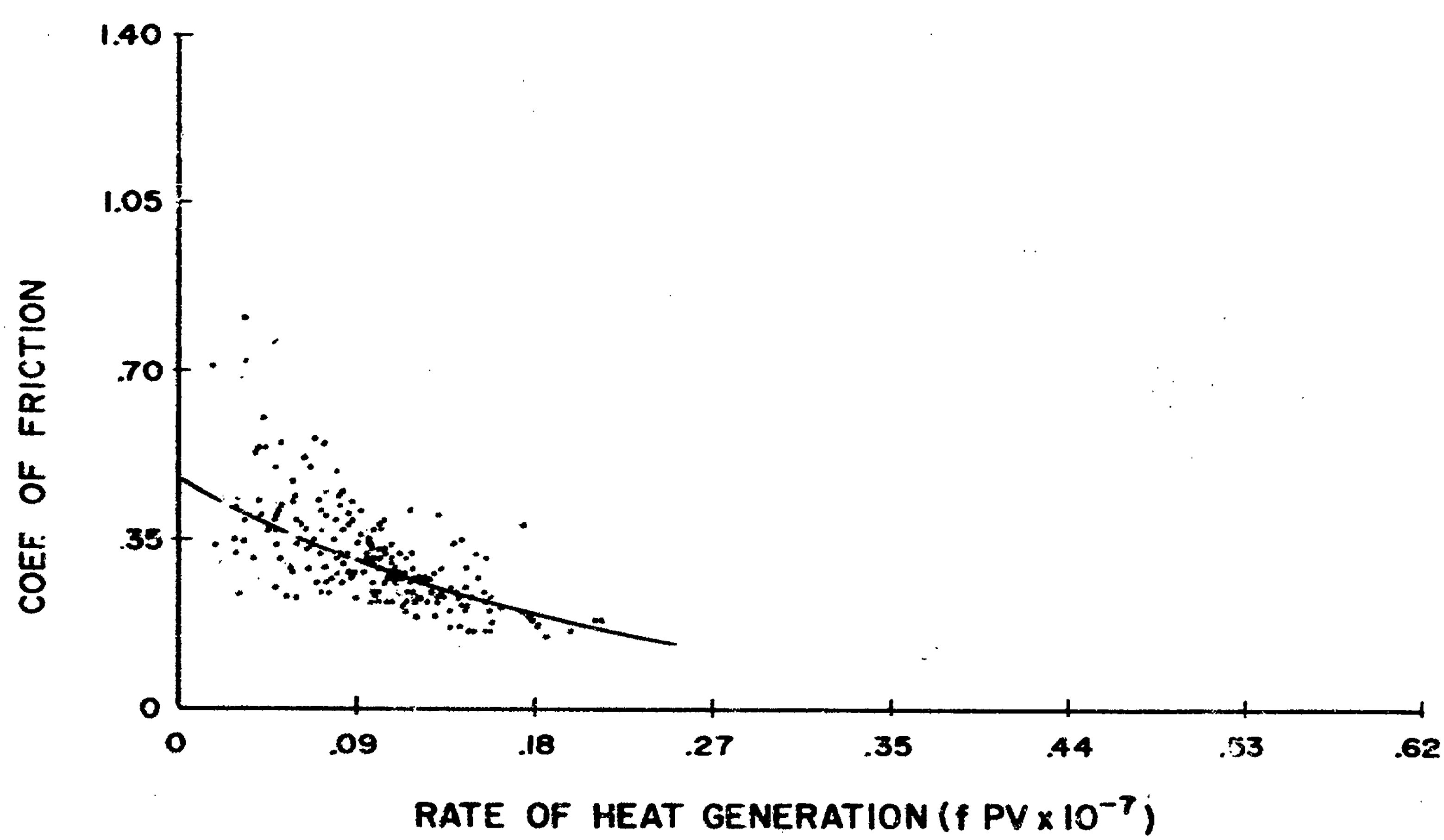

Fig. 6 Coefficient of Friction of Gilding Metal as a Function of Heat Flux (psi) (fps)

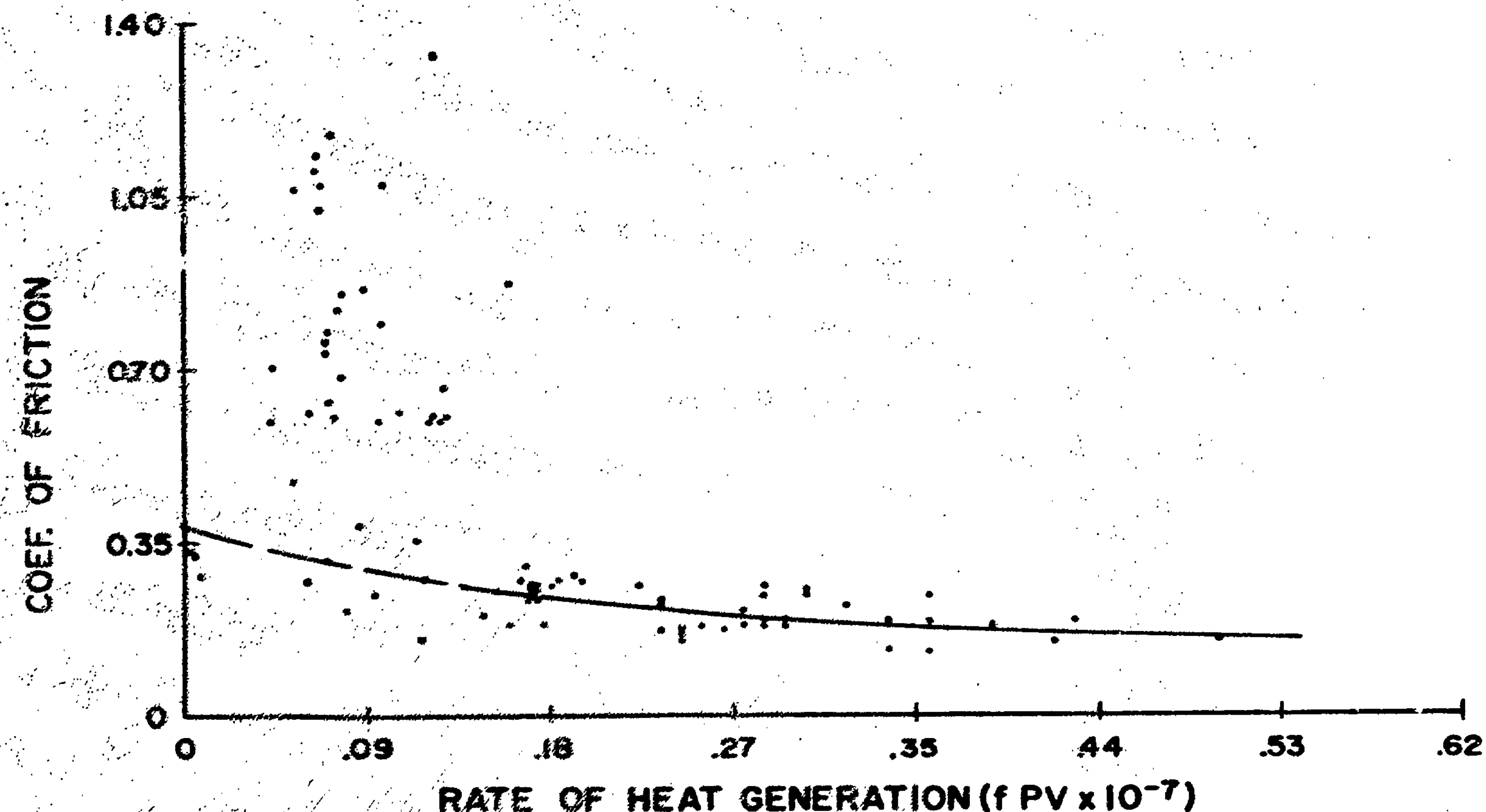

Fig. 7 Coefficient of Friction of Copper as a Function of Heat Flux (psi) (fps)

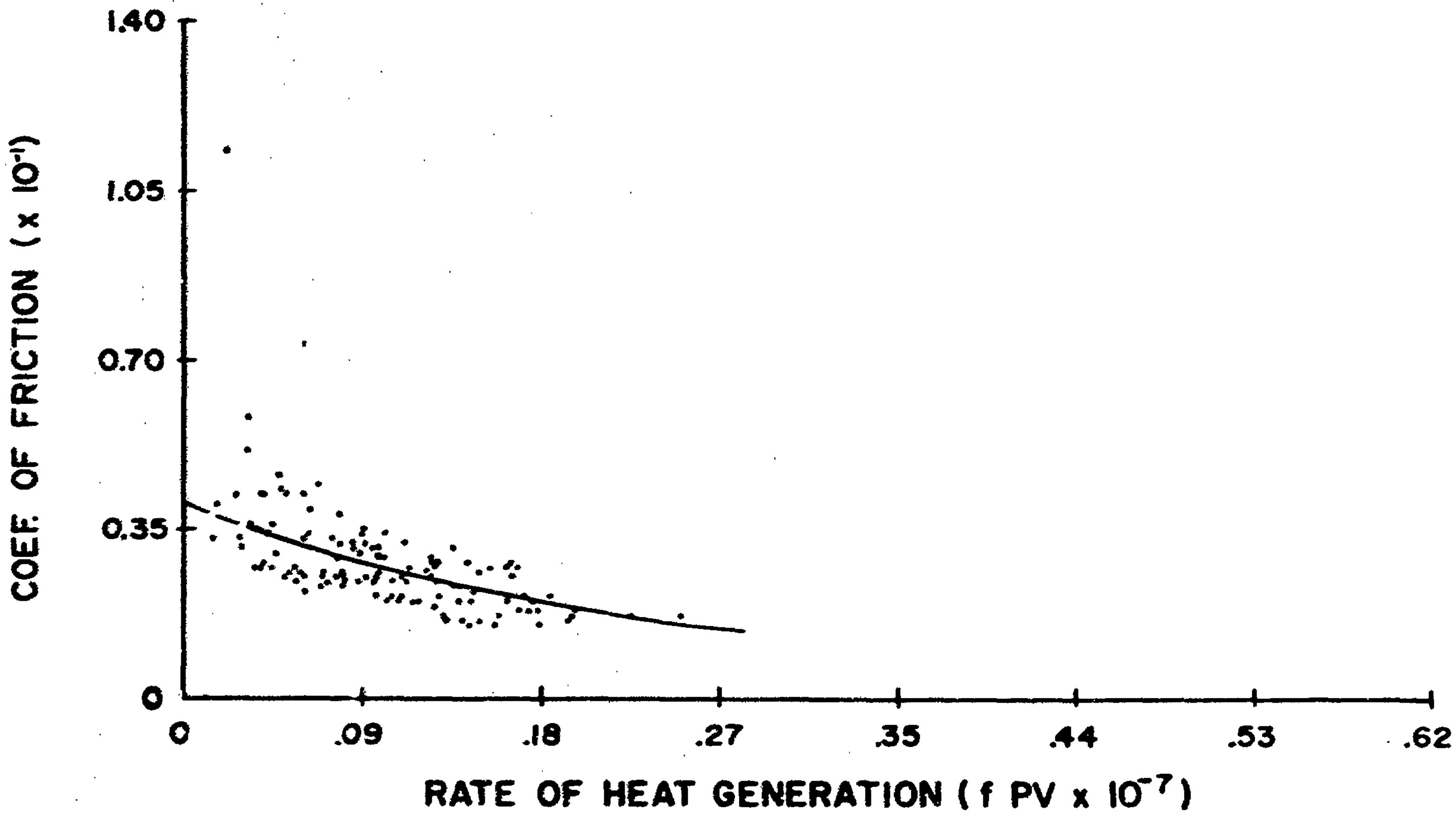

Fig. 8 Coefficient of Friction of Annealed Iron as a Function of Heat Flux (psi) (fps)

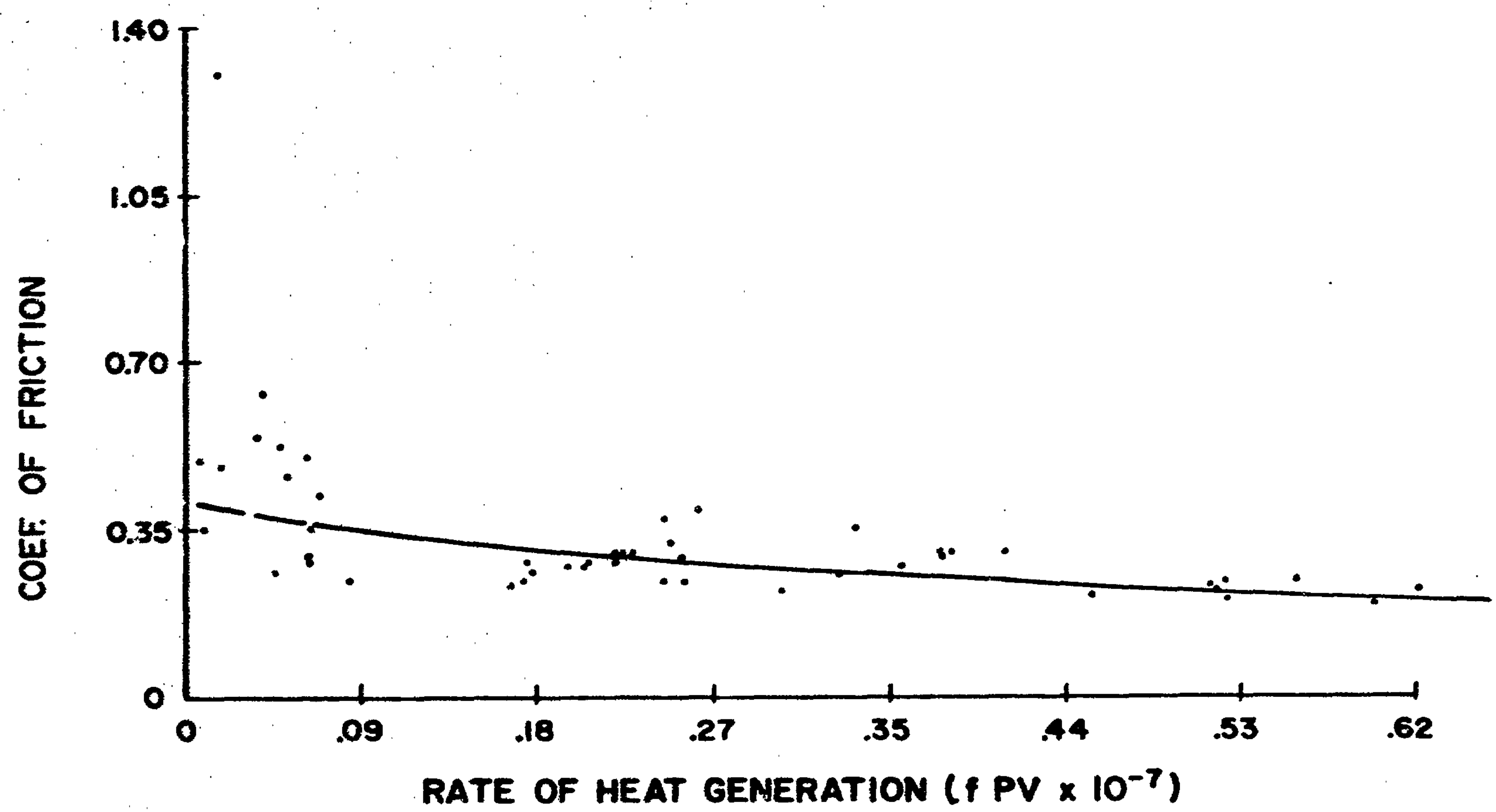

Fig. 9 Coefficient of Friction of Projectile Steel as a Function of Heat Flux (psi) (fps)

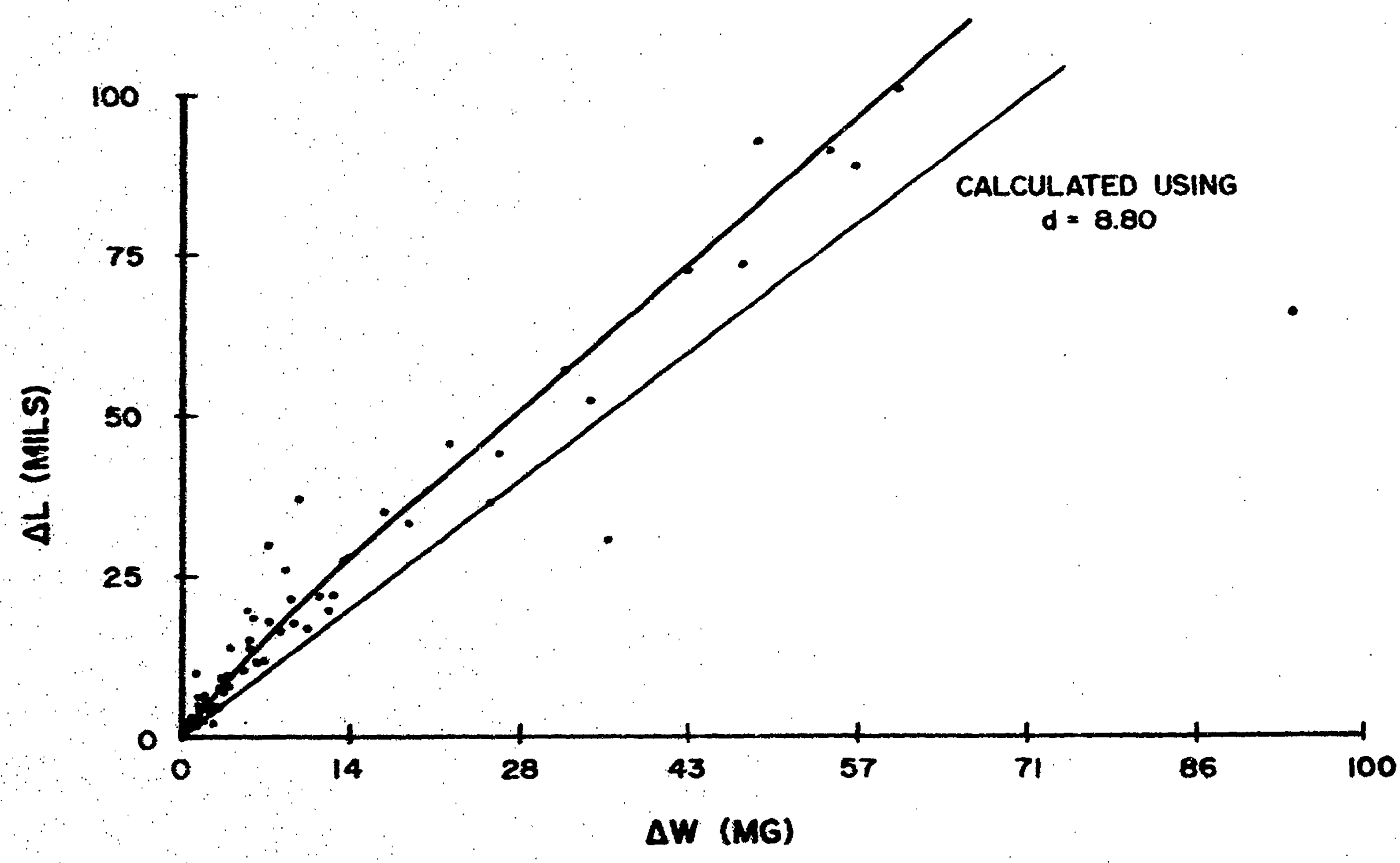

Fig. 10 Length Loss as a Function of Weight Loss for Gilding Metal Pins

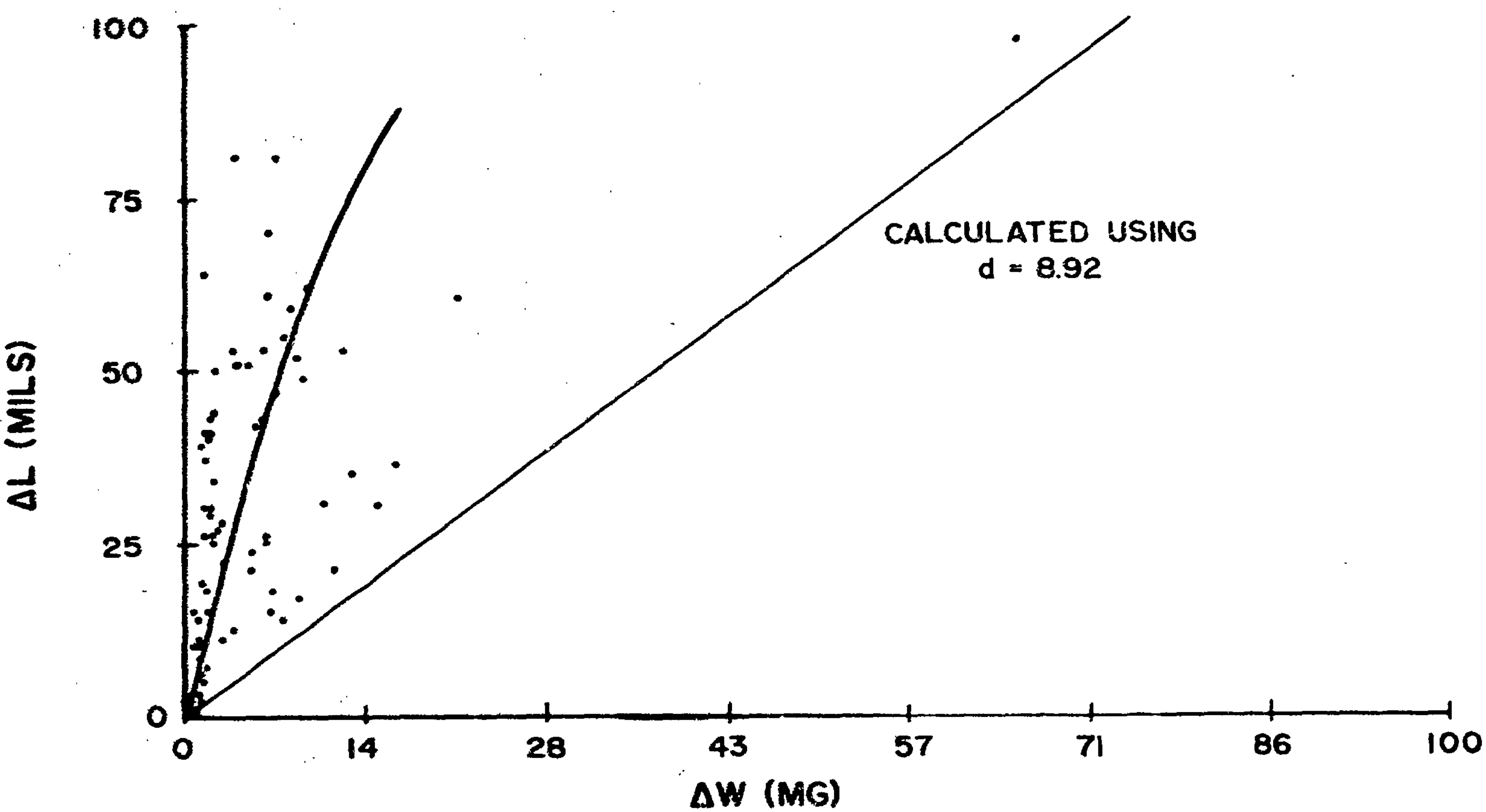

Fig. 11 Length Loss as a Function of Weight Loss for Copper Pins

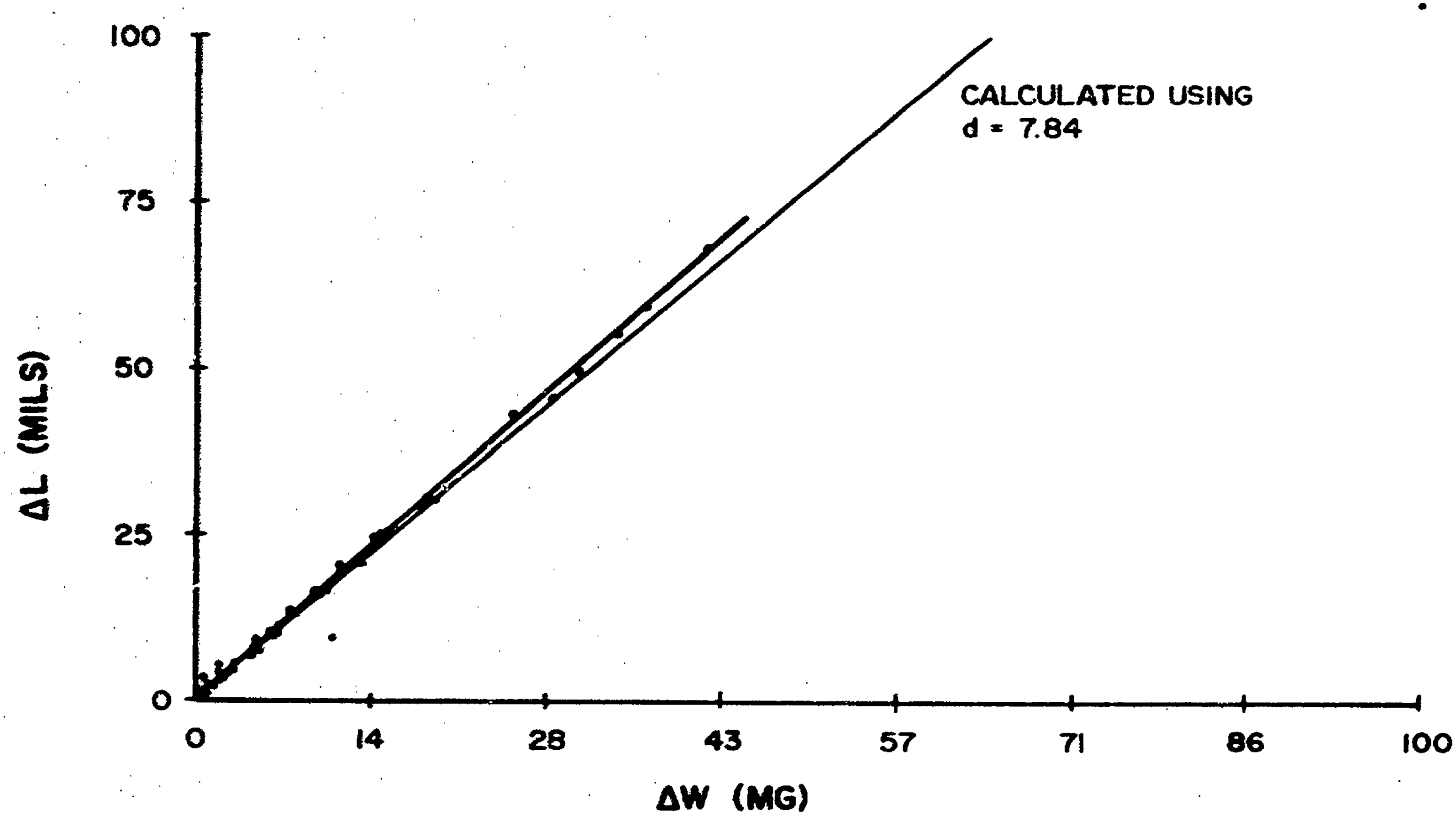

Fig. 12 Length Loss as a Function of Weight Loss for Projectile Steel Pins

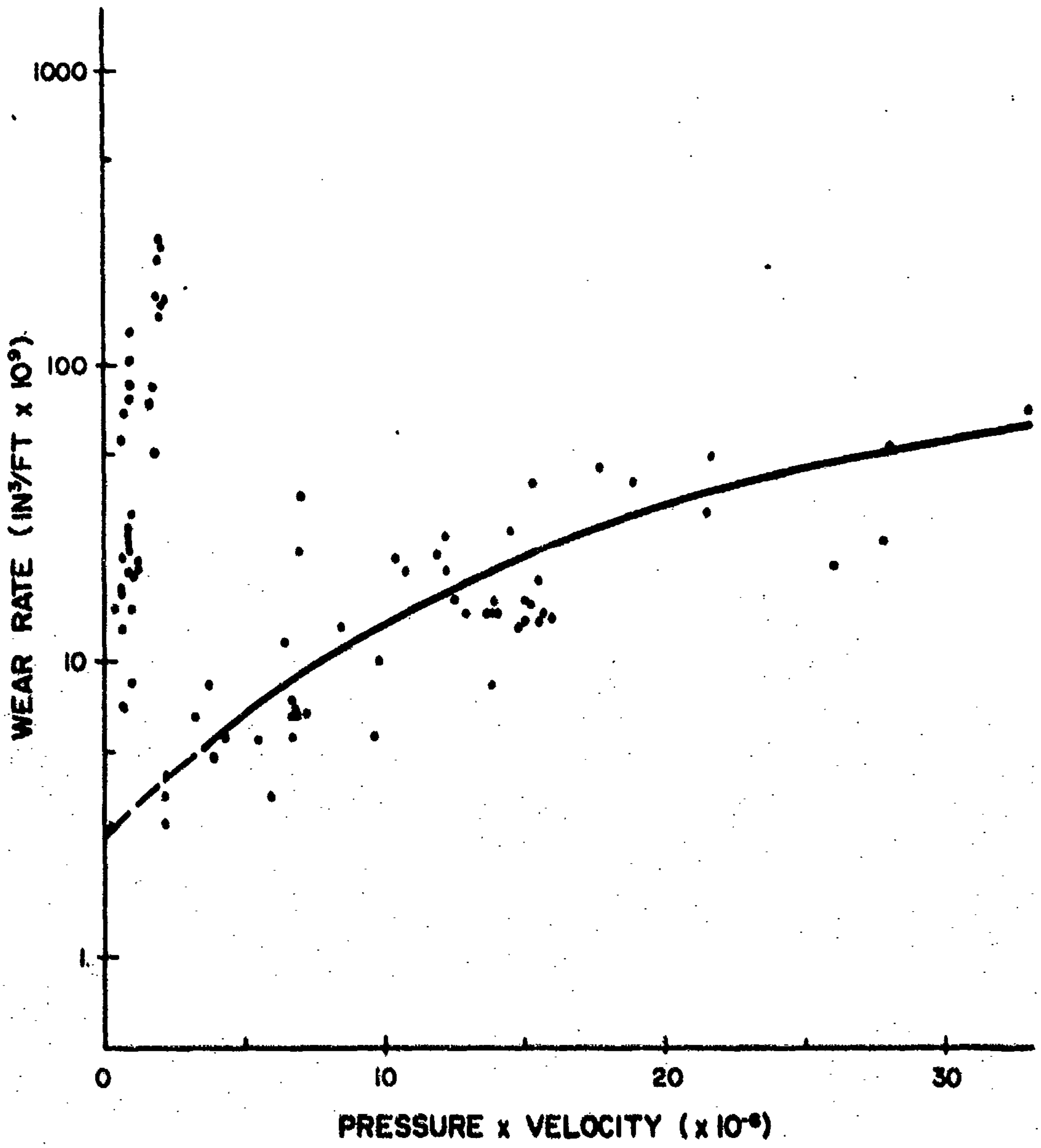

Fig. 13 Wear Rate of Copper as a Function of Pressure x Velocity (psi) (fps)

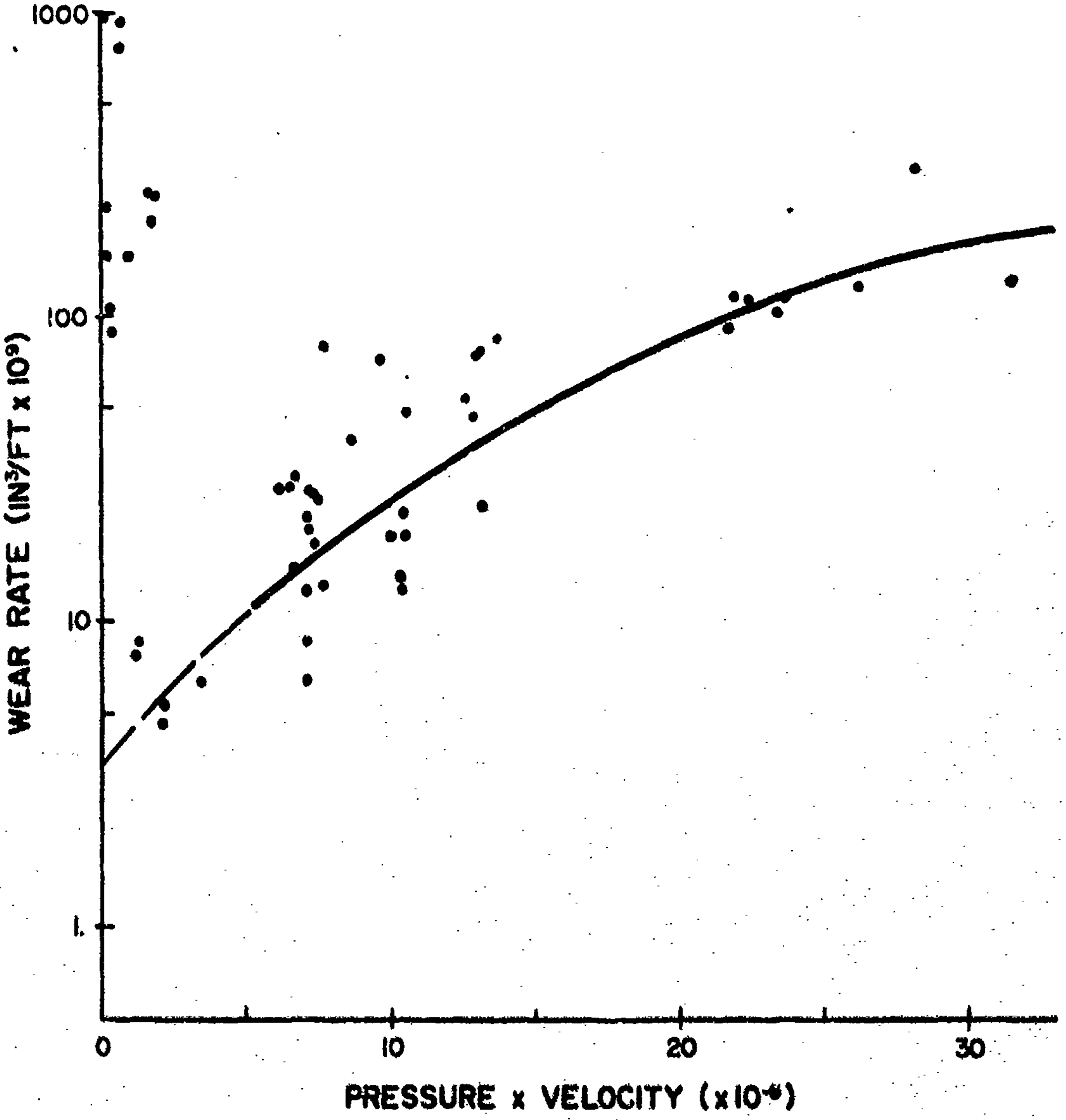

Fig. 14 Wear Rate of Projectile Steel as a Function of Pressure x Velocity (psi) (fps)

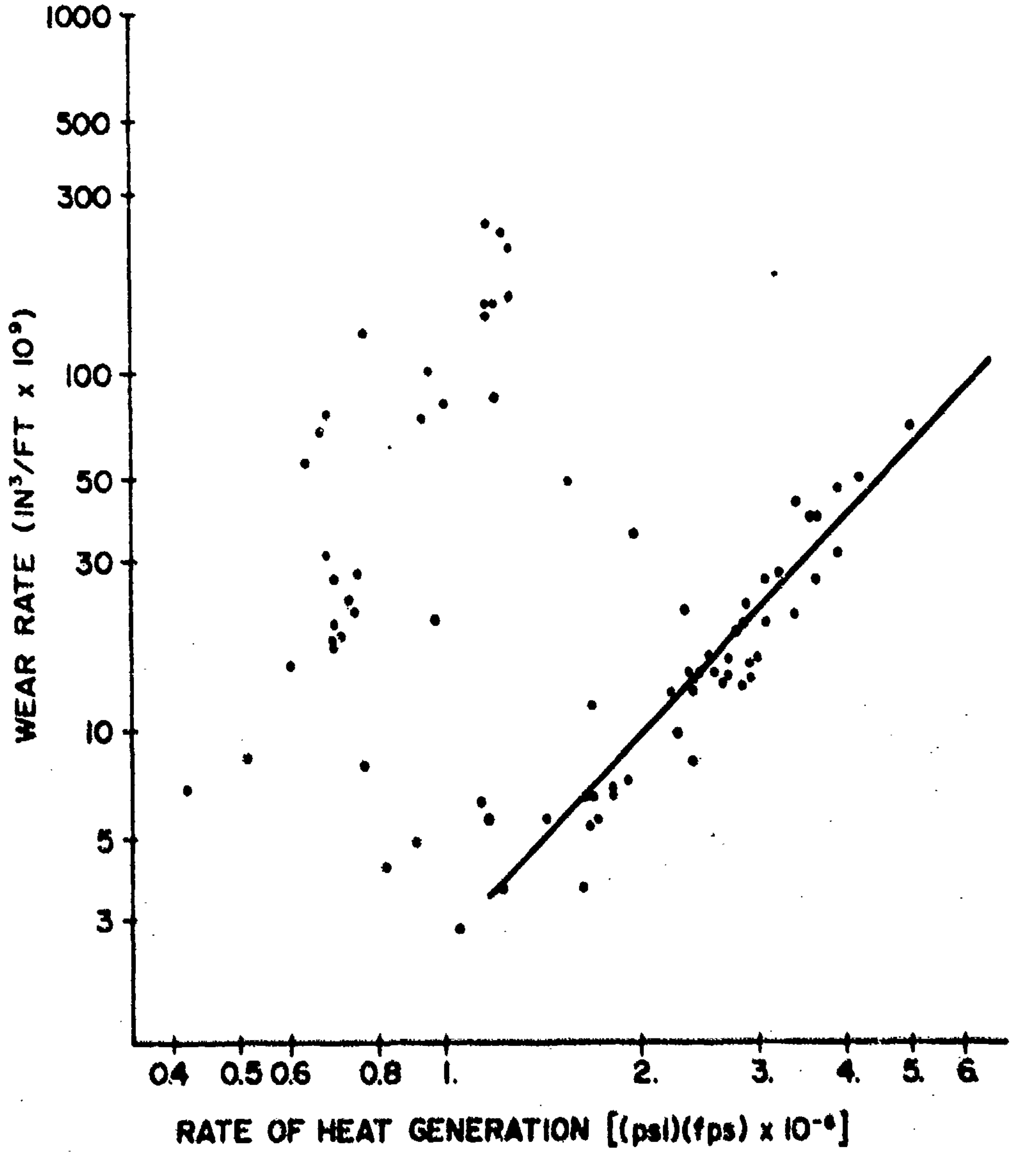

Fig. 15 Wear Rate of Copper as a Function of Rate of Heat Generation (psi)(fps)

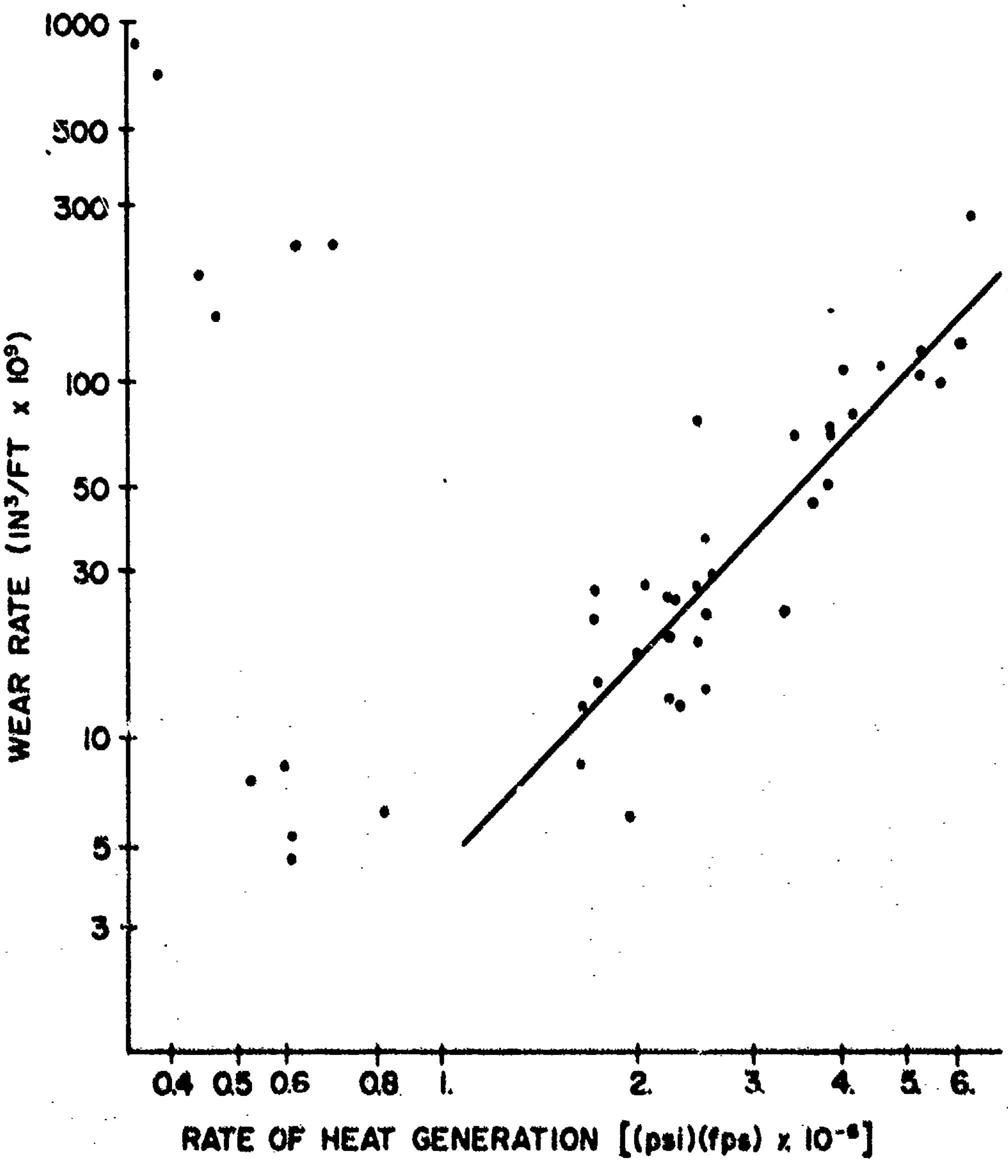

Fig. 16 Wear Rate of Projectile Steel as a Function of Rate of Heat Generation (psi) (fps)

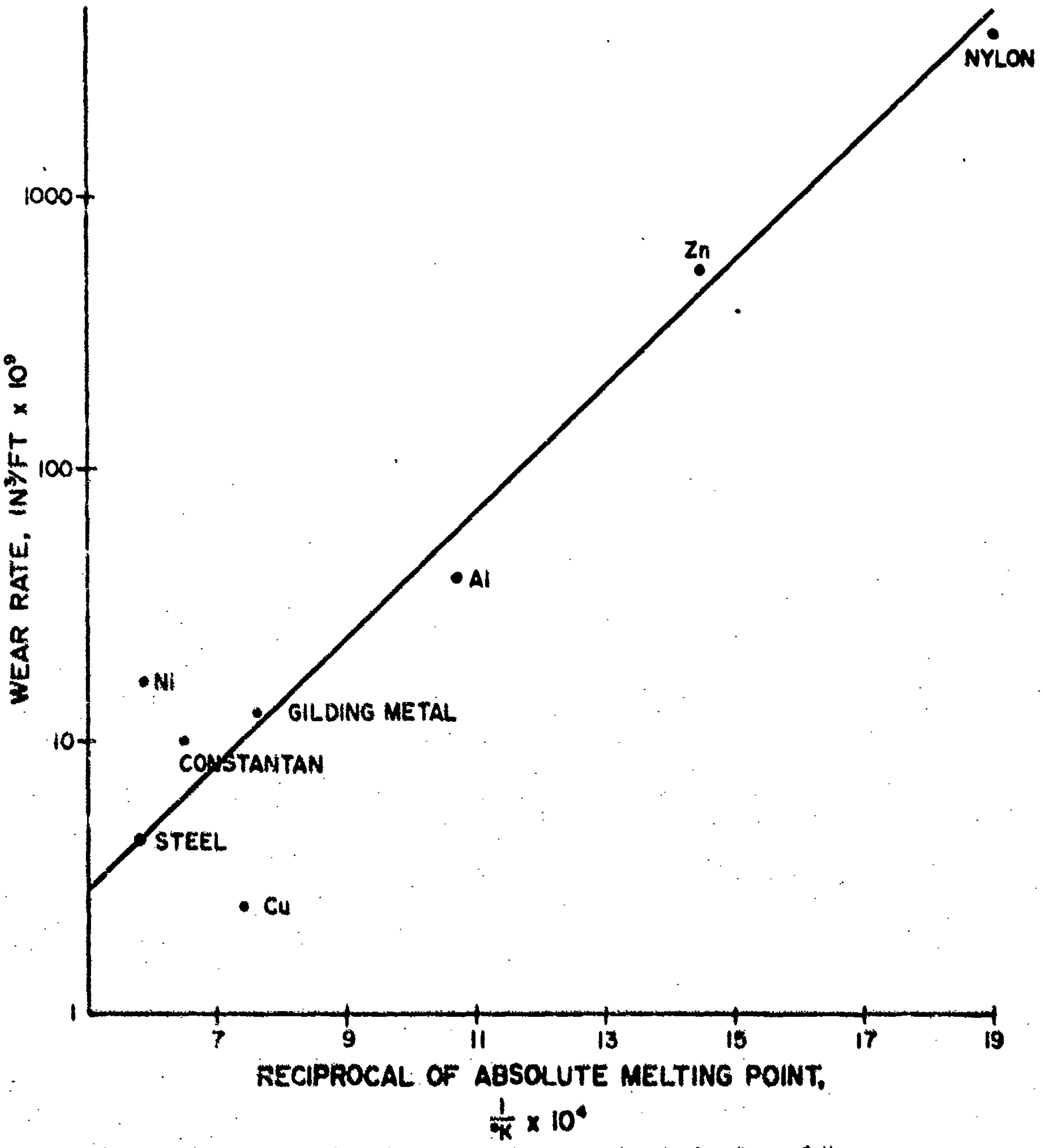

Fig. 17 Wear Rates of Different Materials at a Particular Rate of Heat Generation [fPV = 10^6 (psi) (fps)] as Functions of the Reciprocals of Their Absolute Melting Points

TABLE 1

Chemical Analysis of Gun Steel Friction Disks

Fe(%)	C(%)	Mn(%)	Ni(%)	Cr(%)	Mo(%)	V(%)	Si(%)	P(%)	S(%)
94.4	.35	.59	2.78	.98	.52	.12	.21	.022	.015

TABLE II

Chemical Analyses of Gilding Metal

Lot	Cu(%)	Pb(%)	Zn(%)	Fe(%)	Remainder(%)
No. 1	89.93	.01	9.94	.02	.10
No. 2	90.25	.02	9.65	.03	.05

TABLE III

Chemical Analyses of Annealed Iron

Lot	(Fe(%)	C(%)	Mn(%)	P(%)	S(%)	Si(%)
No. 1	99.922	.017	.020	.008	.023	.010
No. 2	99.934	.023	.018	.007	.017	.001

TABLE IV

Chemical Analyses of Copper

Lot	Cu(%)	Fe(%)	Zn(%)	Al(%)	Ni(%)	Pb(%)	Mn(%)	Sn(%)	Mg(%)
No. 1	Bal.	0.012	.005	0.004	.001	.003	nil	.004	.004
No. 2	Bal.	.006	nil	.002	.0005	.005	nil	.002	.004

Lot	Ag(%)	Cd(%)	Si(%)	Cr(%)	Mo(%)	V(%)
No. 1	.002	nil	.09	nil	nil	nil
No. 2	.008	nil	.03	nil	nil	nil

TABLE V

Chemical Analysis of Projectile Steel

C(%)	Mn(%)	P(%)	S(%)	Si(%)
0.529	0.93	.034	.010	.254

TABLE VI

Chemical Analyses of Miscellaneous Metals

Metal	Cu(%)	Fe(%)	Zn(%)	Al(%)	Ni(%)	Pb(%)	Mn(%)	Sn(%)	Mg(%)
Constantan	54.11	.40	--	--	44.49	.92	--	--	--
Zinc	.0003	.002	Bal.	--	nil	.001	nil	nil	nil
Aluminum	.05	.33	--	Bal.	--	--	.01	--	.02
Nickel	.033	.078	--	.011	Bal.	<.003	.235	--	.037

Metal	Ag(%)	Cd(%)	C(%)	S(%)	Si(%)	Cr(%)	Mo(%)	V(%)	Co(%)	Ti(%)
Constantan	--	--	.074	--	--	--	--	--	--	--
Zinc	nil	.001	--	--	nil	nil	nil	nil	--	--
Aluminum	--	--	--	--	.12	--	--	--	--	--
Nickel	--	<.001	.101	.005	.031	<.002	--	--	.310	.027

TABLE VII

Friction and Wear of Gilding Metal on Gun Steel

Data from References (2), (3), (4), (5), (6) and (7)

Pin diameter is 0.080 in.

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	f PV $x10^{-6}$	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in ^{3}/ft ($x10^9$)
300	6,000	1.8	-	-	18.9	1.3	4.5	4.6
300	2,400	.73	-	-	18.9	0.1	2.0	.35
300	9,800	2.9	-	-	19.8	1.4	5.9	4.8
300	12,300	3.7	-	-	18.6	5.4	19.2	20.1
400	2,400	.96	-	-	19.2	0.6	1.2	2.2
400	6,000	2.4	-	-	18.8	1.1	2.5	4.1
400	8,000	3.2	-	-	18.4	3.3	8.8	12.5
400	11,000	4.4	-	-	18.2	3.9	13.6	15.3
590	3,500	2.0	-	-	18.0	1.5	2.4	5.8
590	6,900	4.1	-	-	17.7	2.0	3.9	7.6
590	10,700	6.3	-	-	18.9	3.8	9.2	14.0
590	17,000	10.0	-	-	18.3	8.6	5.6	32.6
590	13,800	8.2	-	-	17.1	9.1	21.0	36.8
300	19,200	5.8	-	-	15.6	5.9	18.2	26.4
600	20,400	12.2	-	-	16.8	7.3	17.7	30.5
400	9,100	3.6	-	-	16.6	8.2	16.3	34.2
400	7,600	3.1	-	-	25.6	5.6	14.5	15.3
400	8,900	3.6	-	-	33.6	7.2	29.7	14.9
500	5,100	2.6	-	-	23.0	2.9	4.2	8.9
400	14,600	5.8	-	-	19.2	0.4	2.0	1.5
500	8,300	4.2	-	-	19.5	0.9	1.7	3.2
400	6,900	2.8	-	-	19.2	0.7	1.9	2.6
400	13,600	5.5	-	-	19.6	0.5	2.4	1.7
400	19,900	8.0	-	-	19.6	1.0	4.6	3.5
400	16,000	6.6	-	-	19.2	1.4	4.3	5.0
400	3,500	1.4	-	-	19.6	0.4	1.2	1.4
400	4,800	1.9	-	-	19.2	0.5	1.2	1.7
300	6,900	2.1	-	-	19.2	0.6	1.4	2.2
500	6,100	3.0	-	-	19.0	0.6	1.0	2.2
150	12,000	1.8	-	-	19.4	1.4	4.0	5.0
150	18,400	2.8	-	-	18.0	9.7	36.9	37.4
600	11,500	6.9	-	-	18.6	3.8	7.6	14.1
150	4,800	.72	-	-	17.0	16.8	34.8	68.8
150	6,400	.96	-	-	17.6	26.6	44.0	1051
150	3,900	.59	-	-	18.7	2.5	4.4	9.3
300	9,600	2.9	-	-	18.3	3.2	8.6	12.1
300	8,600	2.6	-	-	18.0	1.8	6.1	6.9

TABLE VII (Cont'd)

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	fPV $x10^{-6}$	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in^3/ft ($x10^9$)
300	5,500	1.6	-	-	14.8	25.9	36.4	121
300	6,000	1.8	-	-	16.4	43.6	66.0	184
300	9,200	2.8	-	-	16.5	47.1	73.4	197
300	14,400	4.3	-	-	17.1	42.4	72.4	171
300	18,200	5.5	-	-	15.0	60.1	100.7	277
300	22,700	6.8	-	-	15.8	48.4	92.5	214
300	5,300	1.6	-	-	12.0	3.4	7.0	19.5
300	11,700	3.5	-	-	12.0	19.0	33.0	110
300	19,900	6.0	-	-	12.0	22.4	45.4	130
150	3,000	.45	-	-	11.8	12.2	19.2	71.4
150	6,500	.98	-	-	10.2	34.4	52.3	234
150	12,700	1.9	-	-	10.7	56.6	88.8	366
150	16,300	2.4	-	-	12.0	54.4	91.0	314
400	4,200	1.7	-	-	10.0	6.3	11.2	43.9
400	5,200	2.1	-	-	12.2	2.0	5.4	11.3
400	9,300	3.7	-	-	12.2	5.0	10.0	28.4
400	12,200	4.9	-	-	12.2	11.4	21.5	64.7
400	15,100	6.0	-	-	12.0	13.9	27.6	80.5
400	17,900	7.2	-	-	11.6	35.9	30.4	216
400	21,500	8.6	-	-	11.0	32.2	57.0	203
600	5,200	3.1	-	-	12.0	1.1	2.1	6.3
600	8,400	5.0	-	-	11.1	2.4	3.4	15.1
600	11,300	6.8	-	-	11.7	3.2	7.3	19.0
600	19,300	11.6	-	-	12.0	12.5	21.8	72.2
600	18,400	11.0	-	-	12.0	9.3	17.5	53.8
600	26,300	15.8	-	-	12.0	13.6	27.2	79.0
300	2,600	.79	-	-	15.8	10.4	16.6	45.9
300	3,300	1.00	-	-	10.2	2.5	1.8	16.9
600	3,100	1.8	-	-	10.5	0.8	1.0	5.2
600	2,600	1.5	-	-	10.8	1.9	2.5	12.3
600	2,300	1.4	-	-	11.1	1.2	1.8	7.4
300	2,200	.65	-	-	15.8	6.8	11.5	48.4
600	13,400	8.0	-	-	10.8	6.7	11.5	43.2
600	10,800	6.5	-	-	18.6	5.7	13.4	21.2
300	9,800	2.9	.32	.93	-	-	-	-
300	17,500	5.2	.23	1.20	-	-	-	-
600	6,600	4.0	.34	1.36	-	-	-	-
600	11,300	6.9	.22	1.52	-	-	-	-
600	16,300	9.8	.18	1.76	-	-	-	-
450	6,100	2.7	.37	1.00	-	-	-	-
450	10,800	4.9	.29	1.42	-	-	-	-
450	13,900	6.3	.24	1.51	-	-	-	-
450	6,500	2.9	.33	.96	-	-	-	-
300	14,700	4.4	.26	1.14	9.9	-	63.7	-
300	4,100	1.2	.39	.47	16.3	-	19.1	-
300	9,100	2.7	.35	.94	12.0	-	56.6	-

TABLE VII (Cont'd)

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	f PV $x10^{-6}$	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in^3/ft ($x10^9$)
300	2,300	.69	.53	.37	12.0	-	30.6	-
450	2,700	1.2	.40	.48	11.2	-	3.2	-
450	4,200	1.9	.35	.66	9.6	-	6.0	-
450	9,900	4.5	.28	1.26	9.0	-	12.7	-
450	14,100	6.3	.23	1.45	10.8	-	30.2	-
600	14,100	8.5	.20	1.70	9.5	-	12.9	-
600	9,000	5.4	.24	1.30	10.8	-	12.1	-
600	2,800	1.7	.37	.63	11.8	-	1.3	-
600	4,100	2.5	.32	.80	9.8	-	1.6	-
450	19,200	8.6	.18	1.55	9.0	-	30.6	-
600	19,400	11.6	.18	2.09	11.1	-	31.5	-
300	19,000	5.7	.25	1.42	10.2	-	50.4	-
150	2,900	.44	.72	.32	10.9	-	3.6	-
150	4,100	.62	.76	.47	8.0	-	27.8	-
150	8,200	1.2	.52	.62	8.2	-	50.5	-
150	13,700	2.1	.40	.84	9.0	-	87.2	-
150	19,600	2.9	.32	.93	9.0	-	85.4	-
600	4,800	2.9	.32	.93	16.0	-	6.5	-
600	9,500	5.7	.24	1.37	11.0	-	11.2	-
150	2,700	.40	.81	.32	6.2	-	3.4	-
150	4,500	.68	.60	.41	6.2	-	9.6	-
150	8,800	1.3	.55	.72	9.5	-	43.0	-
150	17,200	2.6	.37	.96	-	-	-	-
450	9,600	4.3	.27	1.16	11.7	-	25.4	-
300	18,600	5.6	.22	1.23	7.9	-	84.3	-
600	19,100	11.5	.18	2.07	12.0	-	43.3	-
300	7,200	2.2	.37	.81	-	-	-	-
300*	8,800	2.6	.39	1.01	-	-	-	-
450*	5,500	2.5	.31	.78	-	-	-	-
450*	6,700	3.0	.28	.84	-	-	-	-
450*	6,800	3.1	.31	.96	-	-	-	-
450*	7,900	3.6	.31	1.12	-	-	-	-
450*	9,900	4.5	.29	1.30	-	-	-	-
450*	10,100	4.5	.29	1.30	-	-	-	-
600*	2,000	1.2	.31	.37	-	-	-	-
600*	5,000	3.0	.33	.99	-	-	-	-
600*	6,300	3.8	.28	1.06	-	-	-	-
600*	8,700	5.2	.24	1.25	-	-	-	-
600*	9,000	5.4	.25	1.35	-	-	-	-
600*	9,500	5.7	.25	1.42	-	-	-	-
600*	11,200	6.7	.23	1.54	-	-	-	-
600*	15,200	9.1	.19	1.73	-	-	-	-
600*	17,500	10.5	.17	1.78	-	-	-	-
450*	12,600	5.7	.23	1.31	-	-	-	-
450*	15,700	7.1	.20	1.42	-	-	-	-
450*	16,900	7.6	.21	1.60	-	-	-	-

TABLE VII (Cont'd)

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	fPV $x10^{-6}$	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in^3/ft ($x10^{-9}$)
300*	9,300	2.8	.34	.95	-	-	-	-
300*	11,300	3.4	.31	1.05	-	-	-	-
300*	13,400	4.0	.29	1.16	-	-	-	-
300*	15,100	4.5	.28	1.26	-	-	-	-
300*	18,300	5.5	.27	1.48	-	-	-	-
300*	3,900	1.2	.41	.49	-	-	-	-
300*	5,900	1.8	.40	.72	-	-	-	-
300*	10,500	3.2	.30	.96	-	-	-	-
300*	12,900	3.9	.27	1.05	-	-	-	-
300*	15,400	4.6	.26	1.20	-	-	-	-
450*	7,300	3.3	.28	.92	-	-	-	-
450*	9,700	4.4	.27	1.19	-	-	-	-
450*	13,400	6.0	.23	1.38	-	-	-	-
450*	14,900	6.7	.21	1.41	-	-	-	-
450*	17,100	7.7	.20	1.54	-	-	-	-
450*	10,200	4.6	.27	1.24	-	-	-	-
300*	4,000	1.2	.42	.50	-	-	-	-
300*	6,300	1.9	.42	.80	-	-	-	-
300*	7,300	2.2	.39	.86	-	-	-	-
300*	7,500	2.2	.39	.86	-	-	-	-
300*	8,500	2.6	.37	.96	-	-	-	-
300*	5,500	1.6	.49	.78	-	-	-	-
300*	9,500	2.8	.41	1.15	-	-	-	-
300*	10,600	3.2	.40	1.28	-	-	-	-
300*	13,200	4.0	.35	1.40	-	-	-	-
300*	15,300	4.6	.32	1.47	-	-	-	-
300*	16,300	4.9	.31	1.52	-	-	-	-
300*	3,200	.96	.50	.48	-	-	-	-
300*	5,500	1.6	.45	.72	-	-	-	-
300*	18,500	5.6	-	-	9.0	-	87.1	-
300*	1,500	.45	.68	.31	-	-	-	-
300*	3,000	.90	.55	.50	-	-	-	-
300*	5,200	1.6	.43	.69	-	-	-	-
300*	7,300	2.2	.38	.84	-	-	-	-
300*	9,000	2.7	.35	.94	-	-	-	-
300*	10,300	3.1	.33	1.02	-	-	-	-
450*	9,200	4.1	.26	1.07	-	-	-	-
450*	10,400	4.7	.24	1.13	-	-	-	-
450*	10,600	4.8	.23	1.10	-	-	-	-
450*	11,400	5.1	.23	1.17	-	-	-	-
450*	11,500	5.2	.23	1.20	-	-	-	-
600*	7,200	4.3	.22	.95	-	-	-	-
600*	11,100	6.7	.20	1.34	-	-	-	-
600*	14,300	8.6	.18	1.55	-	-	-	-
600*	16,100	9.7	.18	1.75	-	-	-	-
600*	2,600	1.6	.31	.50	-	-	-	-

TABLE VII (Cont'd)

Velocity (fps)	Bearing Pressure (psi)	PV (x10^{-6})	f	fPV x10^{-6}	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in ^{3}/ft (x10^9)
600*	4,900	2.9	.24	.70	-	-	-	-
600*	7,200	4.3	.22	.95	-	-	-	-
600*	9,400	5.6	.20	1.12	-	-	-	-
600*	13,100	7.9	.17	1.34	-	-	-	-
600*	15,000	9.0	.16	1.44	-	-	-	-
600*	15,800	9.5	.16	1.52	-	-	-	-
450*	1,800	.81	.39	.32	-	-	-	-
450*	2,600	1.2	.37	.44	-	-	-	-
450*	3,400	1.5	.39	.58	-	-	-	-
450*	5,900	2.7	.30	.81	-	-	-	-
450*	9,200	4.1	.24	.98	-	-	-	-
450*	11,700	5.3	.22	1.17	-	-	-	-
450*	13,800	6.2	.19	1.18	-	-	-	-
450*	14,800	6.7	.19	1.27	-	-	-	-
450*	2,200	.99	.40	.40	-	-	-	-
450*	3,800	1.7	.34	.58	-	-	-	-
450*	5,600	2.5	.29	.72	-	-	-	-
450*	7,200	3.2	.30	.96	-	-	-	-
300*	760	.23	.71	.16	-	-	-	-
300*	3,000	.90	.43	.39	-	-	-	-
300*	6,200	1.9	.33	.63	-	-	-	-
300*	10,700	3.2	.27	.86	-	-	-	-
300*	13,500	4.0	.24	.96	-	-	-	-
300*	15,100	4.5	.24	1.08	-	-	-	-
150*	3,000	4.5	.38	1.71	-	-	-	-
150*	5,200	.78	.54	.42	-	-	-	-
150*	7,700	1.2	.56	.67	-	-	-	-
150*	11,900	1.8	.44	.79	-	-	-	-
300*	2,200	.66	.30	.20	-	-	-	-
300*	5,200	1.6	.38	.61	-	-	-	-
300*	6,400	1.9	.37	.70	-	-	-	-
300*	2,200	.66	.43	.28	-	-	-	-
300*	6,400	1.9	.29	.55	-	-	-	-
300*	7,500	2.2	.29	.64	-	-	-	-
300*	9,400	2.8	.28	.78	-	-	-	-
300*	10,200	3.1	.28	.87	-	-	-	-
300*	2,900	.87	.32	.28	-	-	-	-
300*	4,300	1.3	.50	.65	-	-	-	-
300*	6,100	1.8	.45	.81	-	-	-	-
300*	7,500	2.2	.41	.90	-	-	-	-
300*	8,800	2.6	.38	.99	-	-	-	-
300*	10,200	3.1	.34	1.05	-	-	-	-
300*	11,500	3.4	.32	1.09	-	-	-	-
300*	12,000	3.6	.32	1.15	-	-	-	-
450*	1,600	.72	.54	.39	-	-	-	-
450*	2,800	1.3	.43	.56	-	-	-	-

TABLE VII (Cont'd)

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	fPV $x10^{-6}$	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in^3/in ft ($x10^9$)
450*	4,400	2.0	.39	.78	-	-	-	-
450*	5,500	2.5	.36	.90	-	-	-	-
450*	6,400	2.9	.33	.96	-	-	-	-
450*	7,200	3.2	.31	.99	-	-	-	-
450*	8,200	3.7	.29	1.07	-	-	-	-
450*	8,600	3.9	.28	1.09	-	-	-	-
450*	9,000	4.0	.28	1.12	-	-	-	-
450*	10,100	4.5	.27	1.22	-	-	-	-
300*	2,200	.66	.42	.28	-	-	-	-
300*	4,300	1.3	.44	.57	-	-	-	-
300*	5,700	1.7	.41	.70	-	-	-	-
300*	7,500	2.2	.35	.77	-	-	-	-
300*	8,800	2.6	.34	.88	-	-	-	-
300*	10,200	3.1	.31	.96	-	-	-	-
300*	12,500	3.8	.27	1.03	-	-	-	-
300*	13,100	3.9	.26	1.01	-	-	-	-
300*	2,600	.78	.35	.27	-	-	-	-
300*	4,000	1.2	.47	.56	-	-	-	-
300*	6,600	2.0	.43	.86	-	-	-	-
300*	8,400	2.5	.36	.90	-	-	-	-
300*	10,800	3.2	.32	1.02	-	-	-	-
300*	11,800	3.5	.30	1.05	-	-	-	-
300*	3,000	.90	.35	.32	-	-	-	-
300*	4,700	1.4	.34	.48	-	-	-	-
300*	6,400	1.9	.34	.65	-	-	-	-
300*	8,800	2.6	.32	.83	-	-	-	-
300*	12,200	3.7	.28	1.04	-	-	-	-
300*	13,000	3.9	.27	1.05	-	-	-	-
300*	1,800	.54	.34	.18	-	-	-	-
300*	3,000	.90	.35	.32	-	-	-	-
300*	4,300	1.3	.37	.48	-	-	-	-
300*	6,400	1.9	.34	.65	-	-	-	-
300*	10,100	3.0	.31	.93	-	-	-	-
300*	11,400	3.4	.29	.99	-	-	-	-
300*	12,200	3.7	.28	1.04	-	-	-	-
300*	13,400	4.0	.27	1.08	-	-	-	-
450*	2,600	1.2	.24	.29	-	-	-	-
450*	4,300	1.9	.25	.48	-	-	-	-
450*	5,100	2.3	.23	.53	-	-	-	-
450*	5,600	2.5	.23	.58	-	-	-	-
450*	6,800	3.1	.24	.74	-	-	-	-
450*	8,400	3.8	.23	.87	-	-	-	-
450*	9,400	4.2	.23	.97	-	-	-	-
450*	10,500	4.7	22	1.03	-	-	-	-
450*	11,400	5.1	22	1.12	-	-	-	-
450*	4,900	2.2	.32	.70	-	-	-	-

TABLE VII (Cont'd)

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	f PV $x10^{-6}$	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in ^{3}/in ft ($x10^9$)
600*	8,000	4.8	.22	1.06	-	-	-	-
600*	8,800	5.3	.21	1.11	-	-	-	-
600*	4,700	2.8	.26	.73	-	-	-	-
600*	5,100	3.1	.26	.81	-	-	-	-
600*	7,200	4.3	.22	.95	-	-	-	-
600*	3,400	2.0	.28	.56	-	-	-	-
600*	4,700	2.8	.27	.76	-	-	-	-
600*	6,200	3.7	.26	.96	-	-	-	-
600*	6,800	4.1	.27	1.11	-	-	-	-
600*	8,000	4.8	.24	1.15	-	-	-	-
600*	9,300	5.6	.23	1.29	-	-	-	-
600*	11,400	6.8	.21	1.43	-	-	-	-
600*	4,300	2.6	.26	.68	-	-	-	-
600*	7,500	4.5	.22	.99	-	-	-	-
600*	9,700	5.8	.22	1.28	-	-	-	-
1200*	7,200	8.6	.18	1.55	-	-	-	-
1200*	6,800	8.2	.17	1.39	-	-	-	-
1200*	7,600	9.1	.16	1.46	-	-	-	-
1200*	8,000	9.6	.16	1.54	-	-	-	-
1200*	10,100	12.1	.15	1.82	-	-	-	-
1200*	10,100	12.1	.16	1.94				

* Experiments with gradually increasing loads

TABLE VIII

Friction of Annealed Iron on Gun Steel

Data from References (6) and (7)

Pin Diameter is 0.080 in.

Velocity (fps)	Bearing Pressure (psi)	PV $(x10^{-6})$	f	fPV $x10^{-6}$
450	11,400	5.1	.21	1.07
450	15,000	6.8	.20	1.36
450	6,000	2.7	.22	.59
450	10,800	4.9	.21	1.03
450	20,900	9.4	.15	1.41
300	10,000	3.0	.26	.78
300	15,500	4.6	.24	1.10
300	20,100	6.0	.21	1.26
450	5,800	2.6	.32	.83
450	10,000	4.5	.28	1.26
450	14,400	6.5	.25	1.62
450	19,100	8.6	.21	1.81
300	9,700	2.9	.34	.99
300	15,500	4.6	.27	1.24
300	19,500	5.8	.28	1.62
300*	8,700	2.6	.29	.75
300*	9,700	2.9	.30	.87
300*	10,400	3.1	.31	.96
300*	11,400	3.4	.32	1.09
300*	13,900	4.2	.29	1.22
300*	14,300	4.3	.31	1.33
300*	16,700	5.0	.28	1.40
300*	18,600	5.6	.26	1.46
300*	18,800	5.6	.27	1.51
300*	20,300	6.1	.27	1.65
600*	2,200	1.3	.36	.32
600*	4,000	2.4	.25	.60
600*	8,300	5.0	.20	1.00
600*	10,900	6.5	.19	1.24
600*	11,900	7.1	.20	1.42
600*	15,900	9.5	.18	1.71
600*	19,900	11.9	.16	1.90
150*	8,200	1.2	.34	.41
150*	9,700	1.5	.30	.45
150*	14,600	2.2	.33	.73
150*	18,000	2.7	.31	.84
600*	12,600	7.6	.17	1.29

TABLE VIII (Cont'd)

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	f PV $x10^{-6}$
600*	17,100	10.3	.15	1.54
600*	18,800	11.3	.17	1.92
600*	1,000	.60	.42	.25
600*	13,500	8.1	.16	1.30
600*	14,300	8.6	.16	1.38
600*	15,300	9.2	.17	1.56
600*	16,200	9.7	.18	1.75
600*	17,900	10.7	.18	1.93
300*	2,000	.60	.51	.31
300*	3,000	.90	.42	.38
300*	4,000	1.2	.36	.43
300*	5,900	1.8	.34	.61
300*	7,900	2.4	.32	.77
300*	9,900	3.0	.31	.93
300*	11,800	3.4	.29	.99
300*	14,800	4.4	.28	1.23
300*	19,600	5.9	.27	1.59
150*	6,200	.93	.42	.39
150*	7,400	1.11	.43	.48
150*	9,900	1.5	.44	.66
450*	900	.40	.40	.16
450*	1,800	.81	.33	.27
450*	2,300	1.04	.35	.36
450*	4,000	1.8	.33	.59
450*	6,100	2.7	.31	.84
450*	7,400	3.3	.29	.96
450*	9,200	4.1	.27	1.11
450*	10,300	4.6	.26	1.20
450*	11,500	5.2	.24	1.25
450*	13,100	5.9	.23	1.36
600*	3,300	2.0	.25	.50
600*	5,000	3.0	.25	.75
600*	6,400	3.8	.25	.95
600*	7,100	4.3	.25	1.08
600*	8,100	4.9	.25	1.22
600*	9,700	5.8	.23	1.33
600*	10,800	6.5	.22	1.43
600*	13,400	8.0	.21	1.68
600*	14,300	8.6	.20	1.72
300*	600	.18	1.13	.20
300*	1,800	.54	.58	.31
300*	3,300	.99	.46	.46
300*	4,000	1.20	.42	.50
300*	4,500	1.4	.42	.59
300*	5,200	1.6	.39	.62

TABLE VIII (Cont'd)

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	f PV $x10^{-6}$
300*	6,500	2.0	.38	.76
300*	8,300	2.5	.35	.88
300*	8,700	2.6	.34	.88
300*	9,500	2.8	.32	.90
300*	12,200	3.7	.26	.96
300*	12,900	3.9	.24	.94
300*	1,400	.42	.33	.14
300*	3,000	.90	.31	.28
300*	4,800	1.4	.27	.38
300*	5,500	1.6	.27	.43
300*	6,500	2.0	.26	.52
300*	7,800	2.3	.24	.55
300*	9,800	2.9	.23	.67
300*	10,900	3.3	.24	.79
450*	3,200	1.4	.28	.39
450*	4,500	2.0	.27	.54
450*	5,800	2.6	.26	.68
450*	6,500	2.9	.24	.70
450*	7,600	3.4	.23	.78
450*	10,100	4.5	.21	.94
450*	11,800	5.3	.20	1.06
450*	13,000	5.8	.20	1.16
600*	2,200	1.3	.27	.35
600*	3,700	2.2	.26	.57
600*	4,500	2.7	.25	.68
600*	5,200	3.1	.25	.78
600*	6,000	3.6	.25	.90
600*	7,200	4.3	.24	1.03
600*	9,900	5.9	.23	1.36
600*	13,400	8.0	.20	1.60
600*	15,400	9.2	.18	1.66
900*	6,300	5.7	.20	1.14
900*	10,100	9.1	.16	1.46
900*	11,400	10.3	.15	1.54
900*	13,000	11.7	.15	1.76
900*	14,500	13.0	.17	2.21
900*	16,100	14.5	.17	2.46
900*	4,000	3.6	.24	.86

* Experiments with gradually increasing loads.

TABLE IX

Friction and Wear of Copper on Gun Steel

Data from References (8), (9), (10), (11) and (12)

Pin diameter is 0.080 in.

Velocity (fps)	Bearing Pressure (psi)	PV (x10^{-6})	f	f PV x10^{-6}	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in^3/ft (x10^9)
150	3,300	.50	1.06	.53	13.3	-	24.	-
150	3,800	.57	1.13	.64	12.2	-	42.	-
150	3,700	.56	1.13	.63	12.7	-	38.	-
150	4,100	.62	1.07	.66	6.3	-	26.	-
150	4,600	.69	.59	.41	.2	-	-	-
150	3,800	.57	1.10	.63	6.2	5.0	21.	55.8
150	4,300	.64	1.02	.65	6.2	6.2	25.	69.2
150	6,000	.90	.77	.69	6.1	2.4	27.	27.0
150	6,200	.93	.73	.68	6.1	2.8	28.	31.2
150	11,100	1.7	.61	1.04	5.8	7.0	81.	83.3
150	10,700	1.6	.59	.94	5.9	6.4	70.	74.2
150	13,700	2.1	.59	1.24	1.2	2.8	22.	160.
150	13,100	2.0	.60	1.20	3.0	6.4	61.	147.
150	13,300	2.0	.59	1.18	2.4	9.5	62.	268
150	12,900	1.9	.66	1.25	2.3	7.7	55.	227
150	12,700	1.9	.66	1.25	2.4	6.0	53.	169
150	13,700	2.1	.60	1.26	2.2	8.1	59.	249
600	3,600	2.2	.38	.84	6.8	0.4	1.	4.1
600	6,600	2.2	.27	.59	7.4	0.3	1.	2.8
600	6,600	2.2	.31	.68	5.9	0.3	1.	3.5
600	10,700	6.4	.26	1.7	5.2	0.9	11.	11.7
600	11,000	6.7	.25	1.7	5.3	0.5	15.	6.5
600	11,100	6.7	.27	1.8	6.4	0.6	10.	6.5
600	21,300	12.8	.21	2.7	5.3	1.1	19.	14.3
600	22,900	13.7	.17	2.3	4.3	0.9	14.	14.5
900	13,100	11.8	.24	2.8	17.1	5.9	43.	22.9
900	13,500	12.2	.25	3.0	18.4	5.4	42.	20.1
900	13,500	12.2	.25	3.0	18.4	7.0	47.	26.2
900	13,900	12.5	.24	3.0	1.7	0.4	0.	16.0
900	17,700	15.9	.18	2.9	5.3	1.1	8.	14.1
900	16,900	15.2	.19	2.9	4.4	1.0	3.	15.6
900	16,700	15.0	.19	2.8	5.6	1.1	6.	13.4
900	16,700	15.0	.18	2.7	17.7	4.1	51.	15.8
900	17,100	15.4	.17	2.6	18.2	3.6	53.	13.6
900	17,100	15.4	.18	2.8	17.6	4.8	51.	18.8
1200	4,600	5.5	.30	1.65	5.2	0.4	1.	5.4
1200	6,000	7.2	.23	1.66	8.3	0.8	1.	6.7

TABLE IX (Cont'd)

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	fPV $x10^{-6}$	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in ^{3}/ft ($x10^9$)
1200	11,300	13.6	.19	4.3	5.2	1.1	2.	14.5
1200	11,500	13.8	.17	2.3	5.9	0.7	1.	8.2
1200	12,700	15.2	.24	3.6	11.8	6.7	18.	39.1
1200	21,700	26.0	.13	3.4	4.2	1.3	5.	21.2
1200	23,100	27.7	.13	3.6	4.3	1.6	7.	25.5
1500	12,300	18.8	.19	3.6	15.0	8.8	17.	40.4
900	4,200	3.8	.24	.91	5.8	0.4	0	4.8
900	4,100	3.7	.21	.78	5.9	0.7	0	8.2
150	13,700	2.1	.59	1.24	1.2	2.8	22	161
150	7,200	1.1	.47	.52	6.4	.8	10	8.4
150	8,300	1.2	.60	.72	5.8	1.8	30	21.4
150	2,600	.39	-	-	6.8	1.5	18	15.1
150	6,600	.99	.61	.60	6.0	1.3	30	15.1
150	6,000	.90	.82	.74	6.2	2.1	34	23.4
150	6,000	.90	-	-	6.2	2.2	50	24.7
150	7,600	1.1	.68	.75	6.5	-	22	-
150	8,200	1.2	.79	.95	5.9	1.8	29	20.6
150	7,600	1.1	.63	.69	6.2	1.7	15	18.6
150	4,000	.60	-	-	5.7	1.1	39	13.0
600	5,400	3.2	.35	1.12	1.4	0.5	2	6.3
150	4,000	.60	-	-	6.0	2.0	34	22.7
600	12,700	7.6	.15	1.14	1.1	-	8	-
150	6,000	.90	-	-	4.8	65.4	98	934.
150	6,000	.90	1.33	1.20	6.9	8.7	52	86.5
150	6,000	.90	1.07	.96	6.2	9.2	49	103.
600	11,900	7.1	.27	1.92	1.4	2.8	11	35.7
150	11,900	1.8	.87	1.57	2.0	1.4	26	49.5
100	6,000	.60	.70	.42	6.3	0.4	3	6.9
100	6,000	.60	1.17	.70	7.6	1.3	64	17.1
10	6,000	.06	.33	.020	15.0	-	-	-
20	6,000	.12	.32	.042	15.6	-	-	-
1000	6,000	6.0	.25	1.50	1.5	-	2	-
1000	6,000	6.0	.27	1.62	1.6	0.5	1	3.5
10	11,900	.12	.32	.038	20.0	-	-	-
20	11,900	.24	.28	.067	18.8	0.1	-	2.8
150	6,000	.90	.77	.69	6.9	2.0	25	19.9
150	6,000	.90	.75	.68	5.6	6.2	26	77.0
150	6,000	.90	.85	.76	6.2	13.	35	130
600	23,500	14.1	.17	2.4	8.1	1.7	40	14.3
600	23,100	13.9	.18	2.5	7.9	1.8	41	15.8
600	24,700	14.8	.16	2.4	7.3	1.4	41	13.0
600	26,200	15.7	.15	2.4	7.0	1.5	37	14.3
1200	6,000	7.2	.20	1.44	4.6	0.7	1	5.6
1600	6,000	9.6	.18	1.73	3.1	0.6	2	5.6
600	11,100	6.7	.28	1.88	20.2	2.2	44	7.3
600	16,300	9.8	.23	2.3	25.9	3.8	81	10.0

TABLE IX (Cont'd)

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	f PV $x10^{-6}$	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in ^{3}/ft ($x10^9$)
100	6,000	.60	1.17	.70	5.1	1.3	64	17.5
600	11,900	7.1	-	-	21.0	1.8	43	23.4
900	4,800	4.3	.27	1.16	7.5	.6	2.0	5.6
150	5,800	.87	.86	.87	5.3	2.1	26.4	27.5
10	11,900	.12	.32	.038	-	-	-	-
1500	6,000	8.7	.18	1.57	-	-	-	-
1200	5,700	6.8	.26	1.77	37.6	3.7	12.4	6.9
1200	12,100	14.5	.22	3.2	30.8	12.3	53.0	27.5
1200	17,900	21.5	.18	3.9	11.2	5.1	23.7	31.6
1500	5,600	8.4	.26	2.2	35.1	6.6	15.1	13.0
1500	11,800	17.7	.19	3.4	32.8	21.4	60.6	44.6
1500	18,700	28.0	.15	4.2	14.2	10.8	30.8	52.1
1800	6,000	10.8	.26	2.8	25.9	7.6	13.8	19.9
1800	5,800	10.4	.22	2.3	35.8	11.6	21.2	21.9
1800	12,000	21.6	.18	3.9	23.0	16.4	36.4	48.7
1800	18,400	33.1	.15	5.0	14.6	15.0	30.5	70.7

TABLE X

Friction and Wear of Projectile Steel on Gun Steel

Data from References (9), (10), (11), and (12)

Pin diameter is 0.080 in.

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	fPV $x10^{-6}$	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in ^{3}/ft ($x10^9$)
150	11,300	1.7	.26	.44	5.7	15.0	25	206
600	11,900	7.1	.27	1.92	7.2	.6	3	6.3
900	11,500	10.4	.22	2.99	6.1	1.0	2	12.6
1200	10,900	13.1	.25	3.28	8.3	2.5	4	23.6
1200	10,500	12.6	.30	3.78	4.6	3.1	5	53.4
150	11,700	1.8	.35	.63	1.5	4.8	9	251
900	11,500	10.4	.24	2.50	10.2	1.8	5	14.1
1200	11,100	13.3	.27	3.59	13.6	8.2	13	46.3
600	11,800	7.1	.24	1.70	6.1	1.4	2	21.9
600	11,900	7.1	.23	1.63	16.2	1.8	4	8.6
600	11,900	7.1	.23	1.63	3.7	.6	1	12.6
600	11,100	6.7	.26	1.74	11.2	2.1	3.3	14.7
150	10,900	1.6	.42	.67	3.0	9.7	16.1	254.
900	10,700	9.6	.35	3.36	13.0	11.8	18.9	71.4
1200	10,700	12.8	.30	3.84	19.6	18.2	29.3	72.9
900	11,900	10.5	-	-	24.0	14.7	23.4	48.0
900	11,500	10.4	.24	2.50	21.9	6.3	9.6	22.7
900	11,900	10.5	-	-	18.4	4.5	6.4	19.0
1200	10,900	13.1	.29	3.80	26.6	25.7	43.1	75.3
900	11,100	10.0	.24	2.40	21.0	5.1	7.3	19.0
30	11,900	.36	.48	.17	.36	.4	.0	87.8
60	10,100	.61	.63	.38	.52	5.0	7.6	760.
60	10,900	.65	.54	.35	.64	7.6	13.3	928.
10	12,700	.13	.49	.064	.081	0.1	0.	96.5
20	12,500	.25	.35	.088	.22	0.3	0.	105.
150	6,000	.90	.52	.47	5.6	11.1	9.3	157
30	3,900	.12	1.30	.16	5.7	11.6	20.2	158
30	3,900	.12	1.30	.16	2.7	7.7	13.1	224
300	3,900	1.2	.50	.60	29.0	3.1	4.5	8.6
300	3,700	1.1	.46	.51	13.2	1.3	2.0	7.8
450	16,900	7.6	.32	2.43	9.8	10.0	15.9	80.2
600	12,900	7.7	.28	2.16	13.1	6.1	9.9	13.2
600	12,000	7.2	.28	2.02	14.2	4.9	8.8	27.5
600	5,700	3.4	.24	.82	7.6	0.6	1.0	6.3
600	12,100	7.3	.30	2.19	14.5	4.8	8.1	25.9
600	12,400	7.4	.27	2.00	6.4	1.5	2.1	18.0
600	3,600	2.2	.28	.62	27.2	1.9	2.9	5.4

TABLE X (Cont'd)

Velocity (fps)	Bearing Pressure (psi)	PV ($x10^{-6}$)	f	fPV $x10^{-6}$	Sliding distance (feet)	wt. loss (mg)	Length loss (mils)	Wear Rate in^3/ft ($x10^9$)
600	3,500	2.1	.29	.61	15.5	0.9	0.9	4.6
900	8,300	7.5	.30	2.25	20.7	6.7	10.9	24.9
1200	5,400	6.5	.37	2.40	26.5	9.3	15.0	27.5
1200	11,400	13.7	.30	4.11	32.2	34.2	55.1	83.0
1200	19,400	23.3	.24	5.59	5.4	6.6	10.2	101.
1200	18,200	21.8	.24	5.23	10.6	14.5	24.2	107.
1200	18,100	21.7	.21	4.56	16.3	18.7	30.1	90.2
1200	19,700	23.6	.22	5.19	19.8	28.9	45.4	115.
1200	18,700	22.4	.23	5.15	25.6	36.6	59.1	112.
1200	23,500	28.2	.22	6.20	25.4	99.6	106.	307.
1500	4,400	6.6	.39	2.57	32.2	12.3	19.6	29.8
1500	17,500	26.2	.20	5.24	26.1	41.5	68.2	125.
1800	3,400	6.1	.28	1.71	38.2	13.4	20.5	27.5
1800	4,000	7.2	.30	2.16	42.8	10.6	16.6	19.5
1800	4,800	8.6	.29	2.49	40.0	19.4	30.2	38.5
1800	17,500	31.5	.19	5.98	18.7	31.1	49.4	130.

Table XI

Friction and Wear of Miscellaneous Materials on Gun Steel

Data from References (7) and (8)

Pin diameter is 0.140 in.

Mat'l	Velocity (fps)	Bearing Pressure (psi)	PV $(x10^{-6})$	f	f PV	Sliding distance (feet)	Weight loss (mg)	Length loss (mils)	Wear Rate $(in^3/ftx10^9)$	Est. Wear Rate $fPV=10^6$	M.P. (°K)
Constantan	1200	11,100*	13.3	0.13	1.73	6.4	2.7	1.	30.5	10.2	1553
	900	3,800	3.4	0.22	0.75	5.7	-	1.	-		
	900	4,200	3.8	0.22	0.84	5.9	2.0	1.	24.0		
Zinc	900	11,900*	10.7	0.30	3.21	5.2	10.7	6.	180	536	692
	900	4,000	3.6	0.14	0.50	5.7	7.7	5.	119		
	900	4,000	3.6	0.14	0.50	5.6	9.2	5.	136		
Aluminum	900	3,800	3.4	0.32	1.09	6.0	0.6	1.	22.7	40	933
	900	4,000	3.6	0.30	1.08	6.2	2.0	1.	72.5		
Nylon	900	3,600	3.2	0.09	0.29	5.0	3.8	9.	407	4080	526
	900	3,600	3.2	0.10	0.32	5.1	3.4	13.	376		
Nickel	900	4,100	3.7	0.20	0.74	5.4	0.7	0.	9.1	16.6	1713
Copper**	-	-	-	-	-	-	-	-	-	2.5	1356
Projectile Steel***	-	-	-	-	-	-	-	-	-	4.4	1725
Gilding Metal****	-	-	-	-	-	-	-	-	-	12.8	1318

* Pin diameter is 0.080 in.
** Wear values from Fig. 15
*** Wear values from Fig. 16
**** Wear values estimated from data in Table VII